

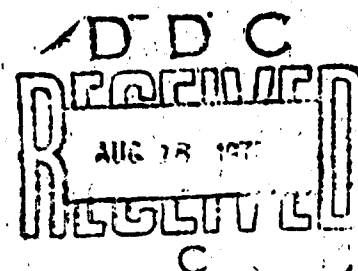
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# Dielectric Constant and Loss Data

W. B. Westphal and A. Sils  
Massachusetts Institute of Technology

Technical Report AFML-TR-72-39

April 1972



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DIELECTRIC CONSTANT AND LOSS DATA

W. B. Westphal and A. Sils


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## FOREWORD

This report was prepared by the Massachusetts Institute of Technology, Laboratory for Insulation Research, Cambridge, Massachusetts, under USAF Contract F33615-71C-1274. This Contract was initiated under Project No. 7371, "Exploratory Development in Electrical, Electronic, and Magnetic Materials," Task No. 737101, "Dielectric Materials." The work was administered under direction of the AF Materials Laboratory, with Mr. W.G.D. Frederick (AFML/LPE) acting as project engineer.

This report was compiled from February 1, 1971 to January 31, 1972, and was submitted in February 1972 by the authors for publication.

This technical report has been reviewed and is approved.

  
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Chief, Electromagnetic Materials Br.  
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Air Force Materials Laboratory

#### ABSTRACT

The main body of this report includes data on high-temperature materials, primarily organic crystals, ceramics and glasses. Additional sections include plastics and materials with less heat resistance.

This report is mainly a recompilation of data on dielectric materials measured after Vol. VI of Tables of Dielectric Materials, 1958. Data from progress reports and the following L.I.R. and Air Force technical reports are included: Tech. Rep. 114, Tech. Rep. 182, Tech. Rep. 203, AFML-TR-65-396, AFML-TR-70-138, AFML-TR-71-66.

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## DIELECTRIC PARAMETERS

Dielectric parameters in the present report have the following notation:

$\kappa'$ ,  $\epsilon'/\epsilon_0$ , dielectric constant relative to vacuum

$\kappa''$ ,  $\epsilon''/\epsilon_0$ , dielectric loss factor relative to vacuum

$\tan \delta$ , or  $\tan \delta_d$ , dielectric loss tangent (dissipation factor)

$\kappa'_m$ ,  $\mu'/\mu_0$ , magnetic permeability relative to vacuum

$\kappa''_m$ ,  $\mu''/\mu_0$ , magnetic loss factor

$\tan \delta_m$ , magnetic loss tangent

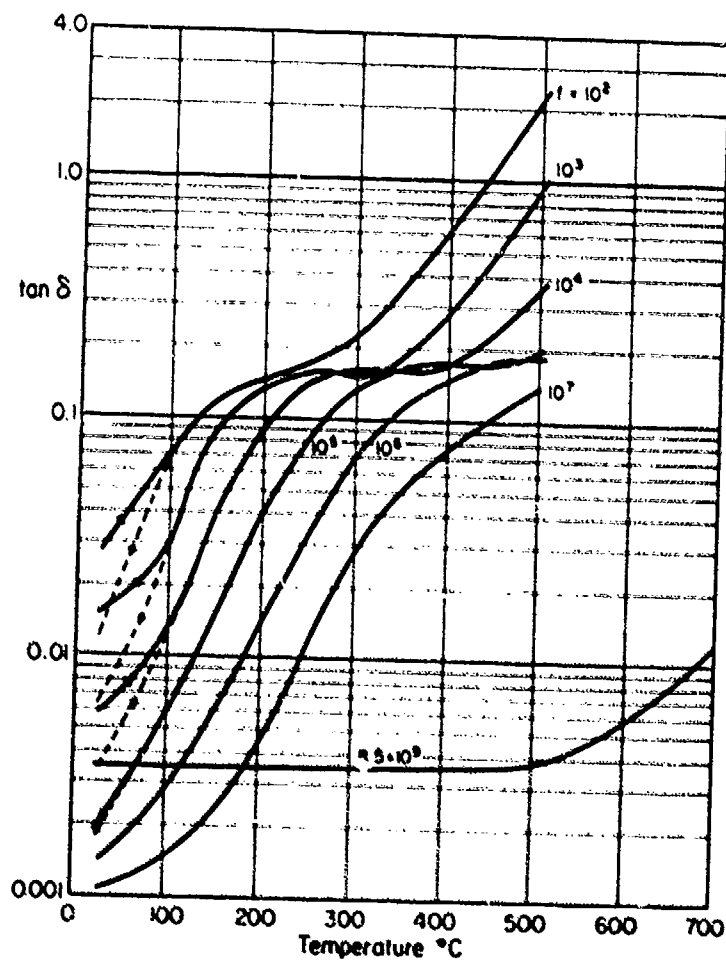
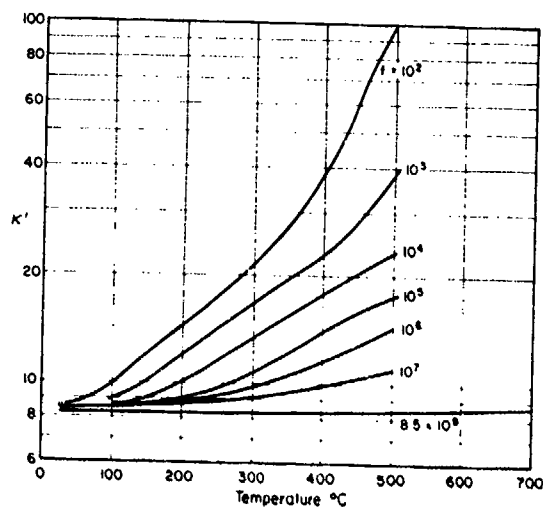
$\sigma$ , a.c. volume conductivity in mho-cm

$\rho$ , a.c. volume resistivity in ohm-cm

# I. INORGANIC COMPOUNDS

Aluminum nitride, hot-pressed,  
at 8.5 GHz, 25°C,  $\kappa' = \pm 0.1$

The Carborundum Co.

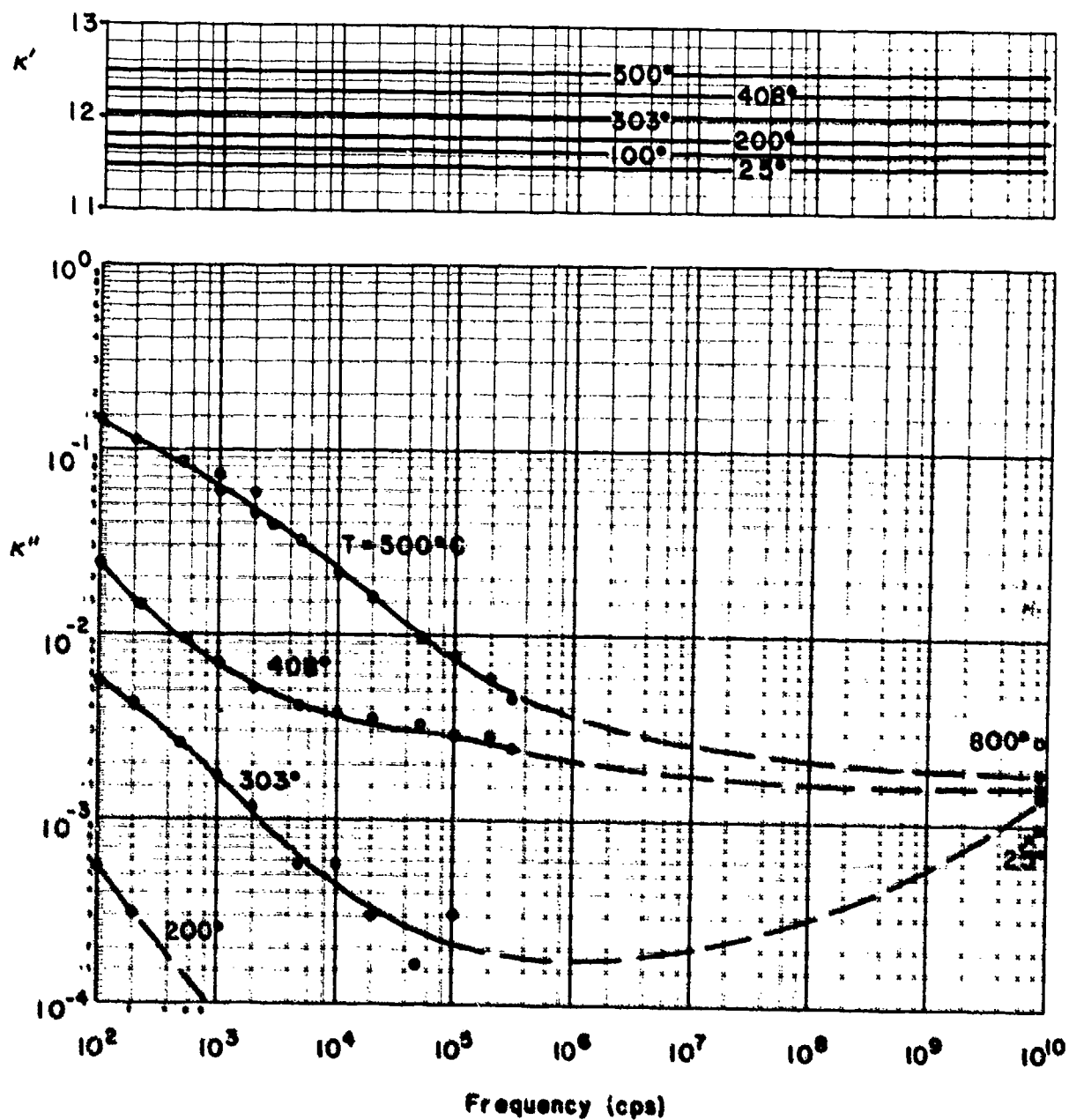




$\text{Al}_2\text{O}_3$  single-crystal sapphire, low frequency  
 peak dispersion due to silver diffusion.  
 To be re-evaluated to higher temperatures  
 with platinum electrodes.

The Linde Air Products Co.

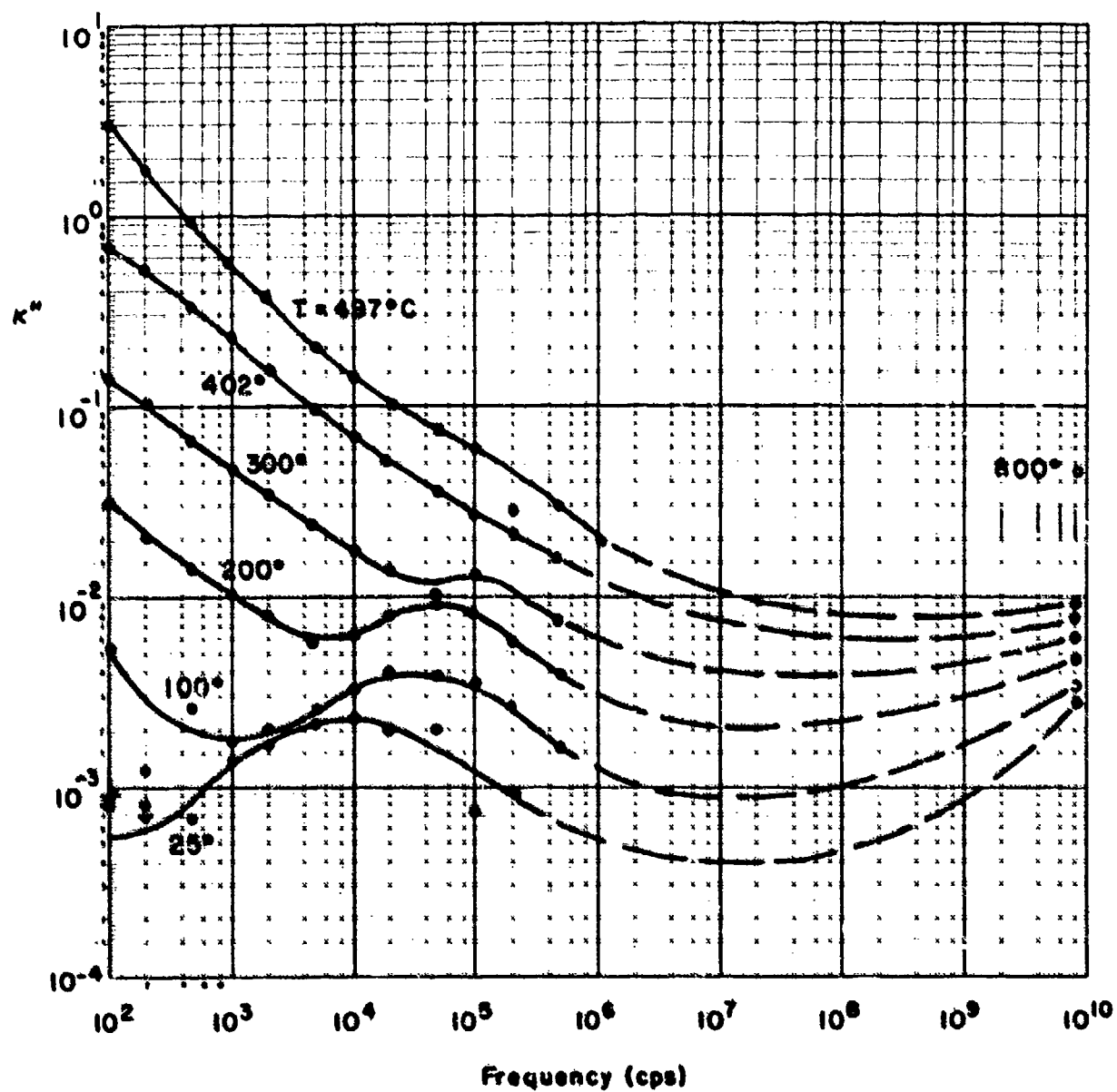
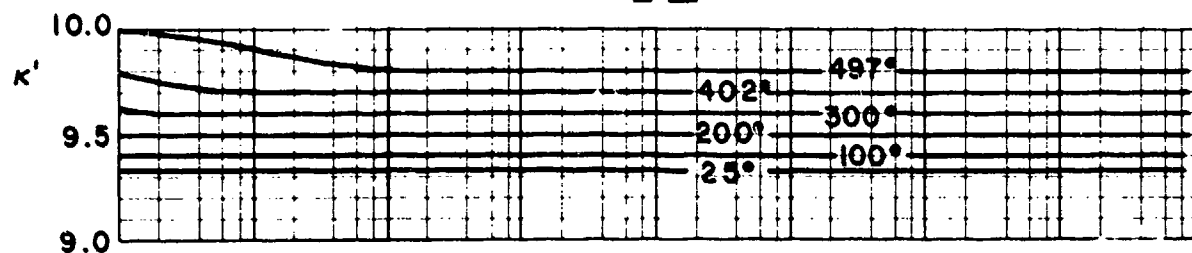
E II



$\text{Al}_2\text{O}_3$  single-crystal sapphire

Linde Air Products Co.

$E \perp$



Aluminum oxide, single crystal

Sapphire  $\text{Al}_2\text{O}_3$

Density at 25°C = 3.9840 g/cm<sup>3</sup>

Union Carbide  
Electronics Division

Loss tangents at 8.5 GHz, 25°C:

$E \perp c$ , <.00002

$E \parallel c$ , <.00005

Freq. 3.45-3.33 GHz,  $E \perp c$

Dielectric constants at 3 GHz:

T°C	$E \perp c$	$E \parallel c$	T°C	$\kappa$	$\tan \delta$
25	9.390*	11.584*	25	9.39	< .0001
-75	9.292	11.433	80	9.41	< .0001
-195	9.257	11.357	240	9.49	< .0001
			377	9.62	< .0001
			526	9.83	< .0001
			617	9.95	< .0001
			713	10.08	< .00015

Variation of dielectric constant at 25°C with inclination of electric field direction with respect to optic axis was calculated from elliptic polarization function:

$$\kappa = \left[ \frac{11.584^2 \times 9.39^2 (1 + \cot^2 \theta)}{11.584^2 + 9.39^2 \cot^2 \theta} \right]^{1/2}$$

$\theta$	$\kappa$
0	
10	11.494
20	11.246
30	10.895
40	10.507
50	10.1295
60	9.820
70	9.584
80	9.439

Average  $\kappa$  for random oriented full-density ceramic:

$$\kappa_{av} = 10.071 \text{ from } \kappa_{av} = (9.39 \times 11.584)^{1/3}$$

or 10.121 for approximate value  $(11.584 + 2 \times 9.390)/3$ .

\* These values are in reasonable agreement with optically measured values of 11.56 and 9.406 [E.E. Russell and Bell, J. Opt. Soc. Am. 57, 543 (1967)].

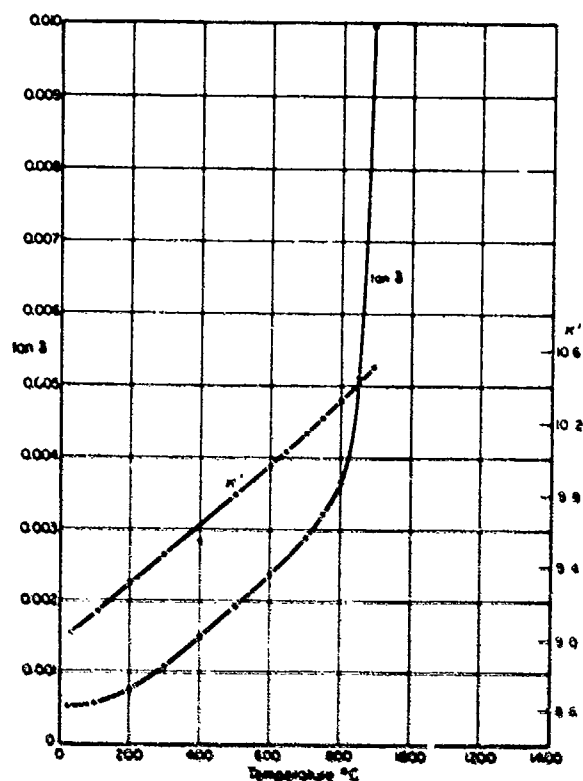
Aluminum oxide  
Multicrystalline (alumina)

Alberox Corp. A-950

95%  $\text{Al}_2\text{O}_3$

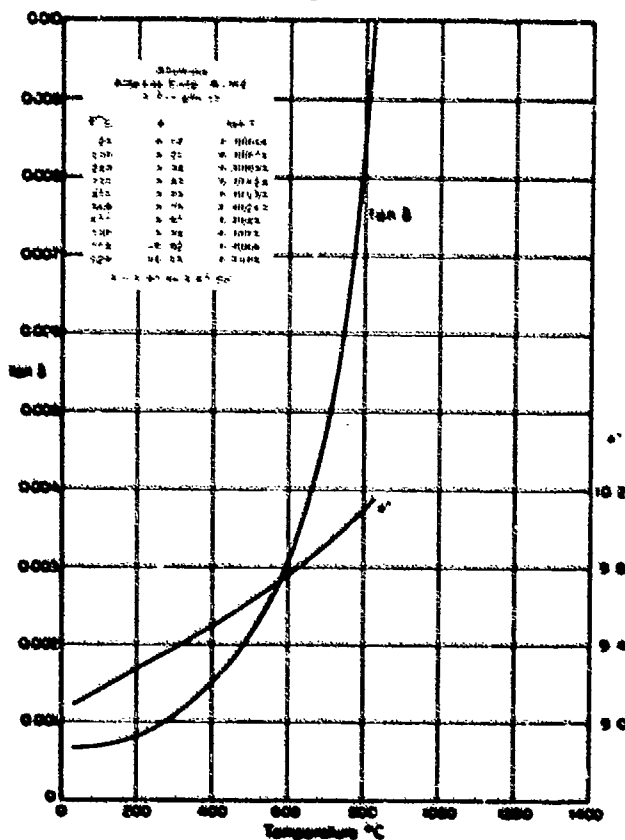
density: 3.663 g/cm<sup>3</sup>

T °C	K'	tan δ
25	9.01	.00051
100	9.14	.00055
200	9.30	.00074
300	9.46	.00108
400	9.53	.00149
500	9.79	.00192
600	9.95	.00237
700	10.13	.00288
750	10.22	.00320
800	10.31	.00367
850	10.41	.0051
892	10.50	.010
3.89 - 3.61 GHz		
25	8.98	.00058
8.5 GHz		



Alberox Corp. A-962

96.2%  $\text{Al}_2\text{O}_3$



Alberox Corp. A-935

93.5%  $\text{Al}_2\text{O}_3$

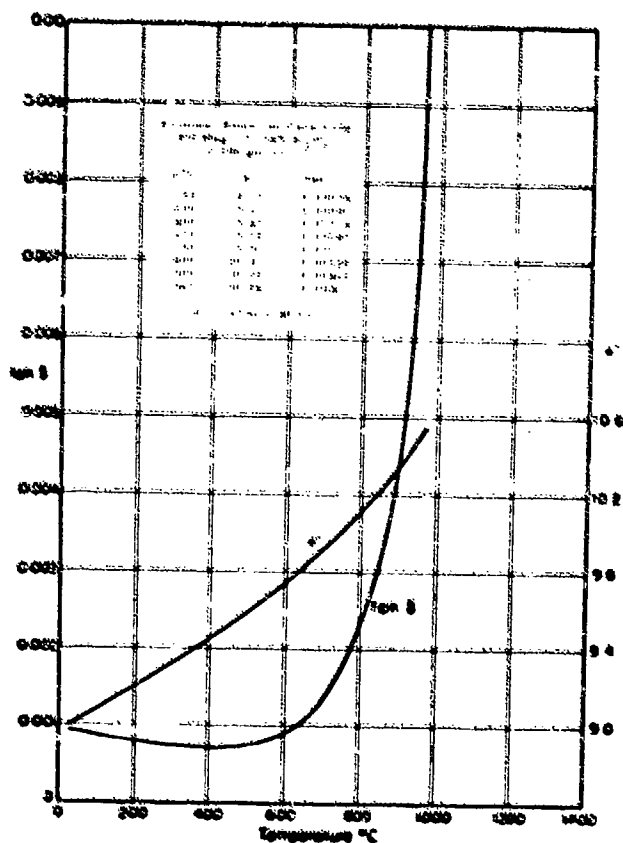
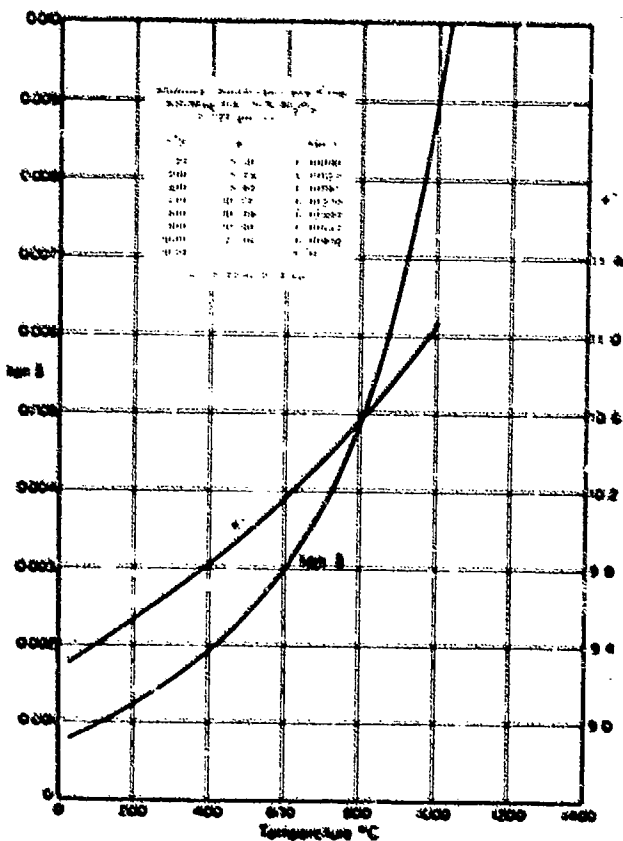
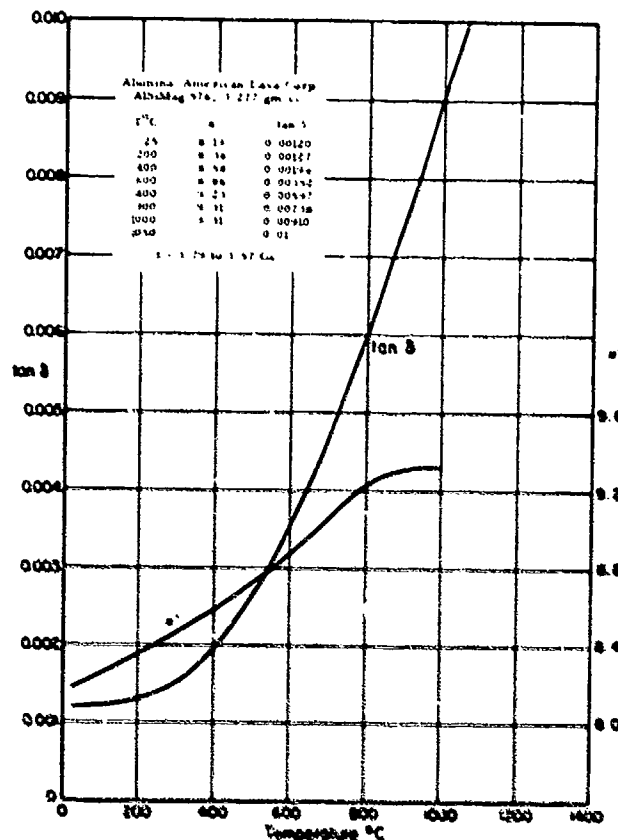
Density 3.623 g/cm<sup>3</sup>

8.52 GHz

T °C	K'	tan δ
25	8.65	.00155
100	8.73	.00208
200	8.84	.00305
300	8.95	.00423
400	9.06	.0057
500	9.18	.0081
540	9.24	.010

# Alumina (cont.)

American Lava



Alumina, high-purity

Armour Research Foundation

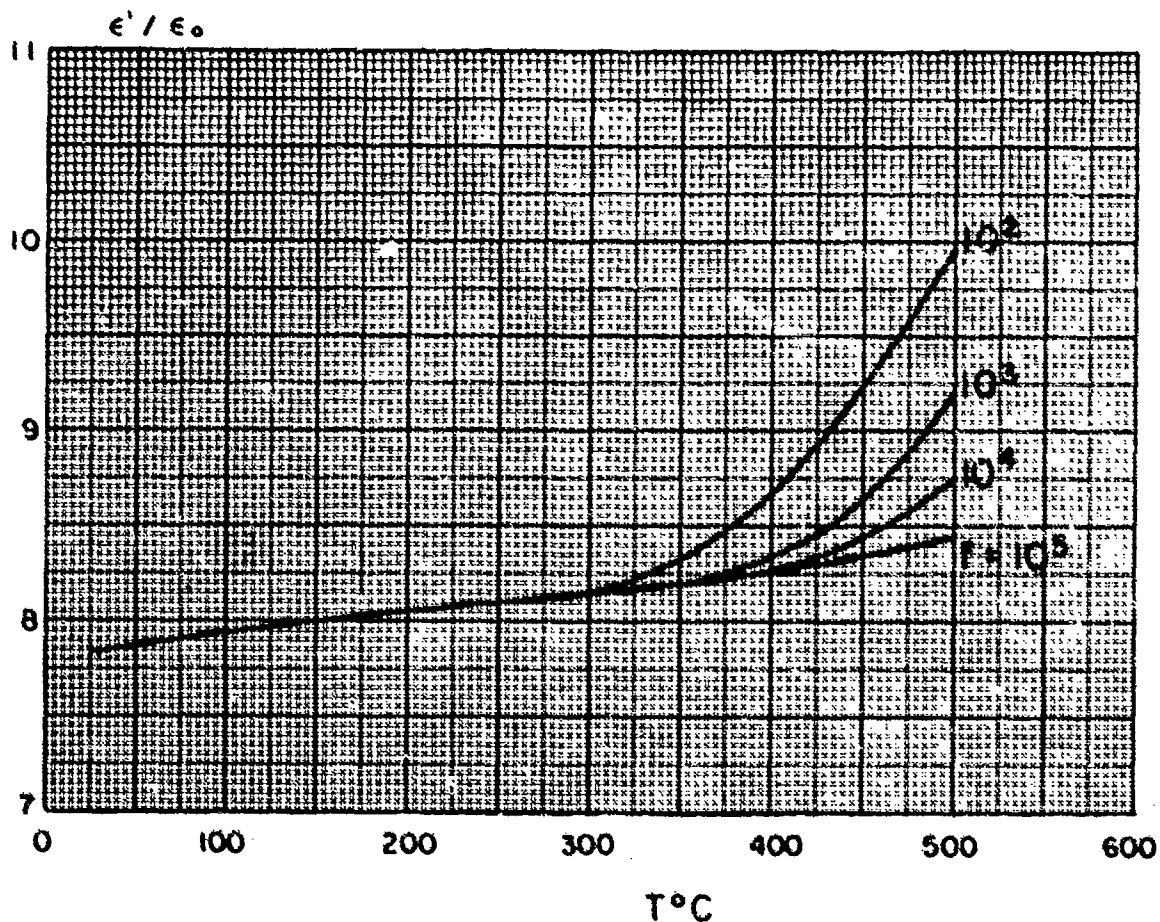
From Alcoa 99.99% Al with HF, fired air 1820°C

Spectrographic analysis: concentration of elements in  
parts per million:

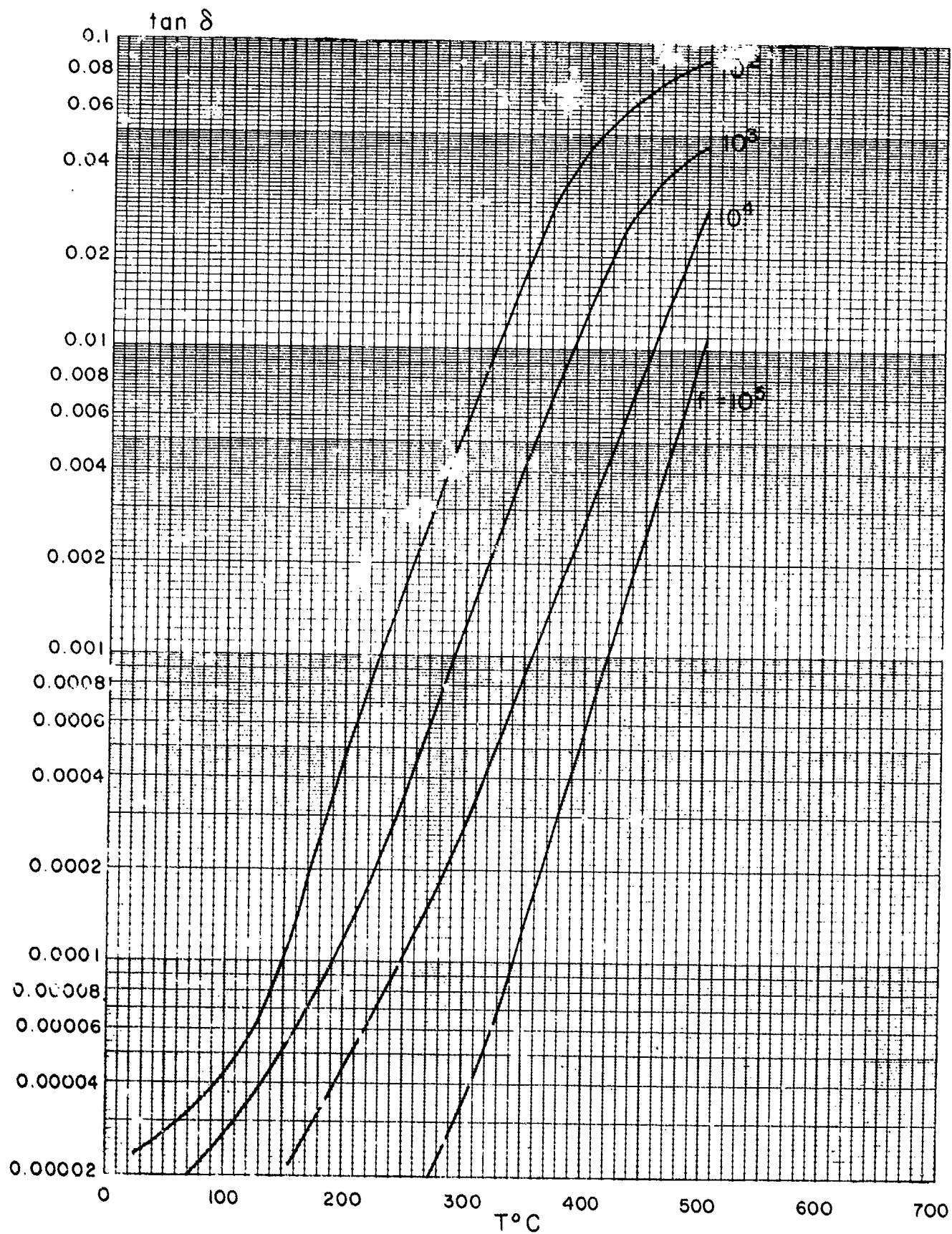
Si	Mg	Fe	Ca	Cu
111	58	38	3	5

Density 3.32 g/cm<sup>3</sup>

Fired silver electrodes



Density 3.32



Alumina, high-purity

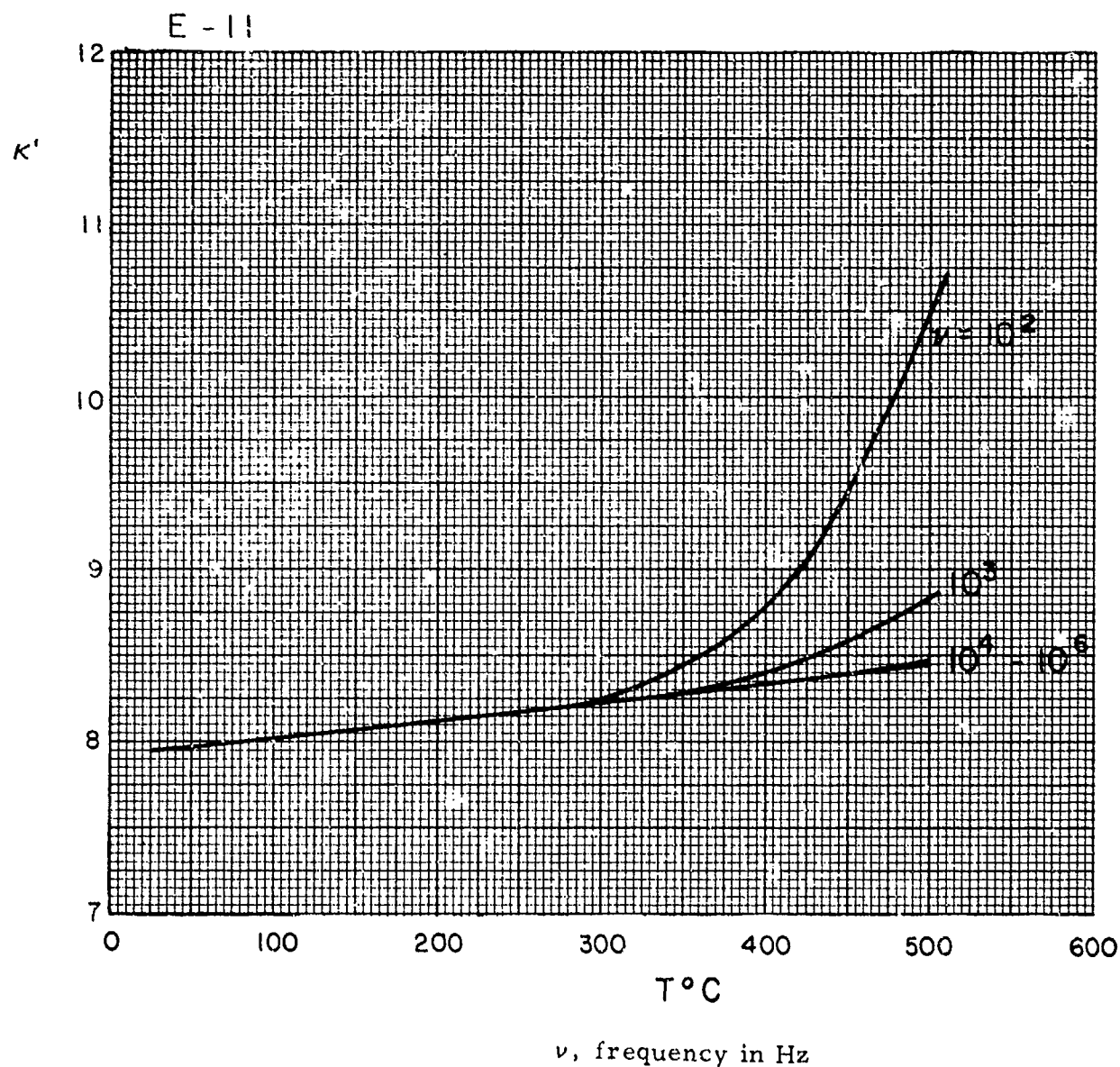
Armour Research Foundation

From Reynolds 99.999% Al with HF, fired air 1840°C

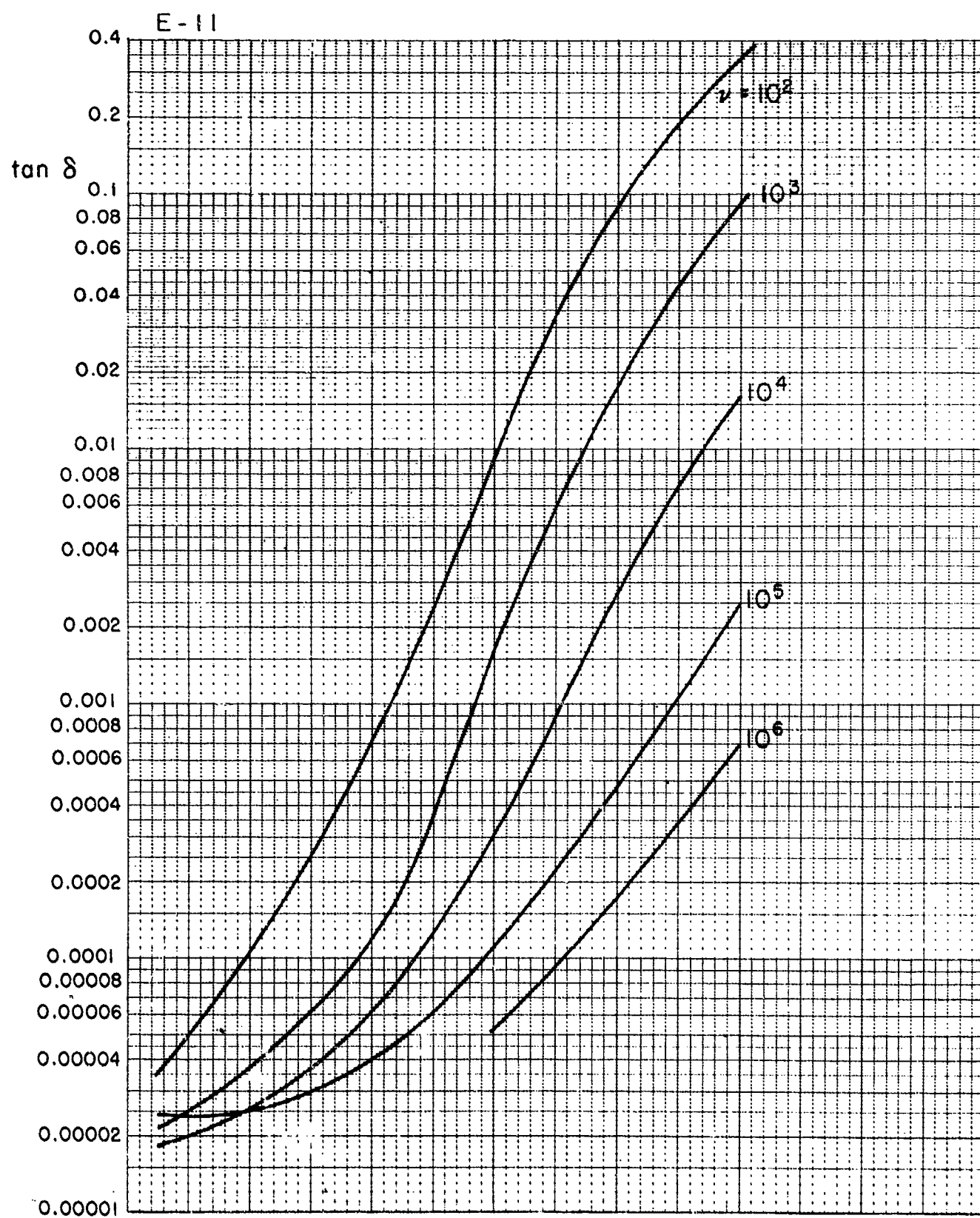
Spectrographic analysis: concentration of elements  
in parts per million:

Si	Mg	Fe	Ca	Ni	Cr	Cu
60	30	60	15	5	4	3

Density 3.23 g/cm<sup>3</sup>







Alumina oxide with added silicic acid

Armour Research Foundation

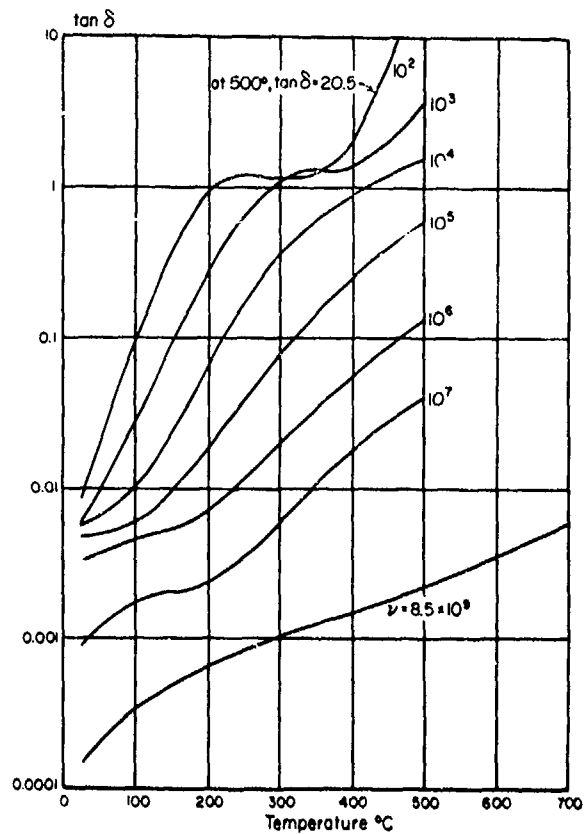
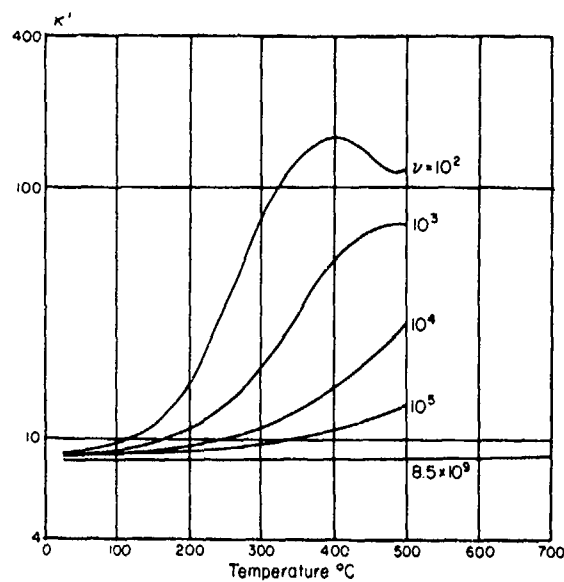
Fired air 1890°C

850 ppm Si, 550 ppm Na

Fired silver electrodes

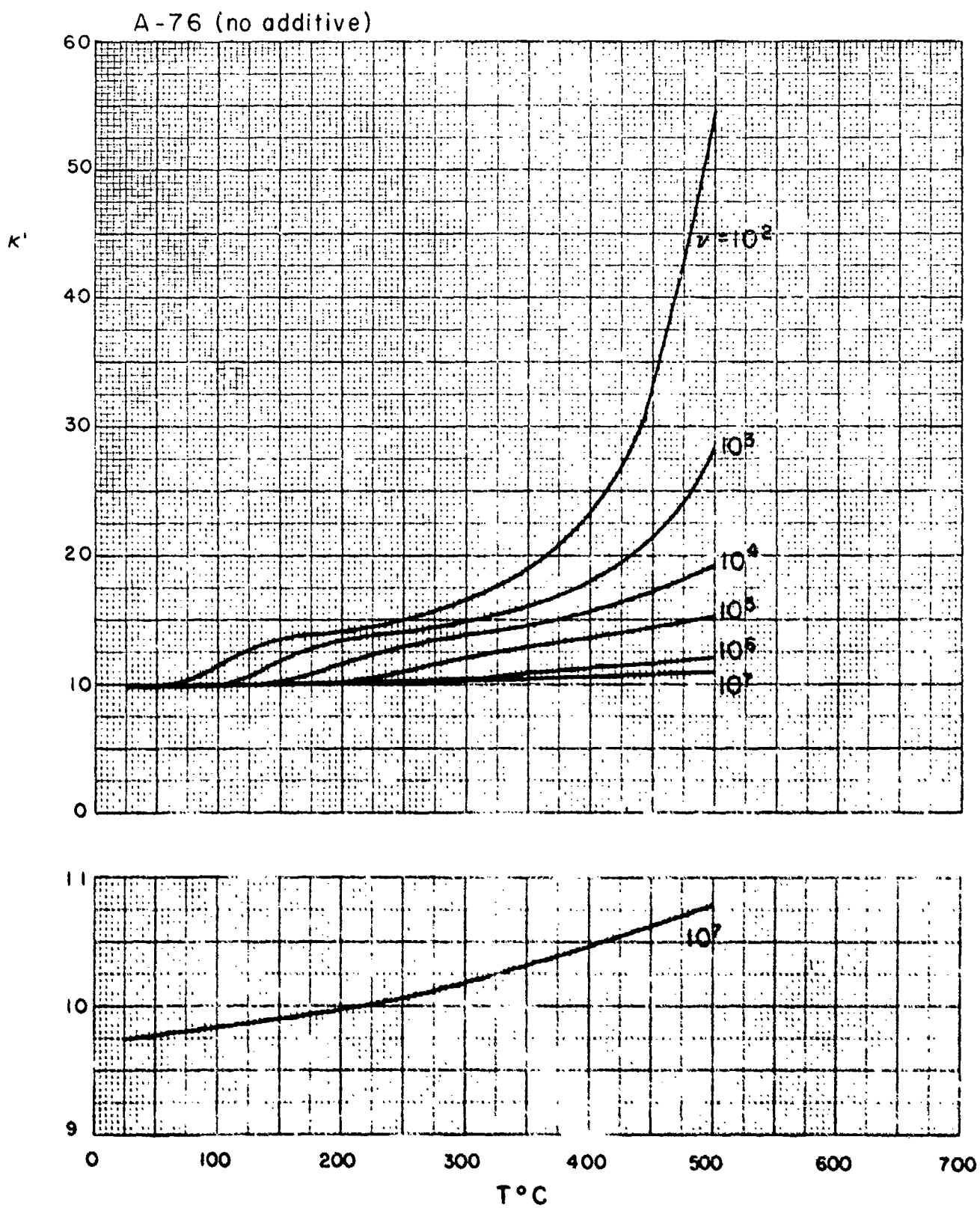
Density 3.49 g/cm<sup>3</sup>

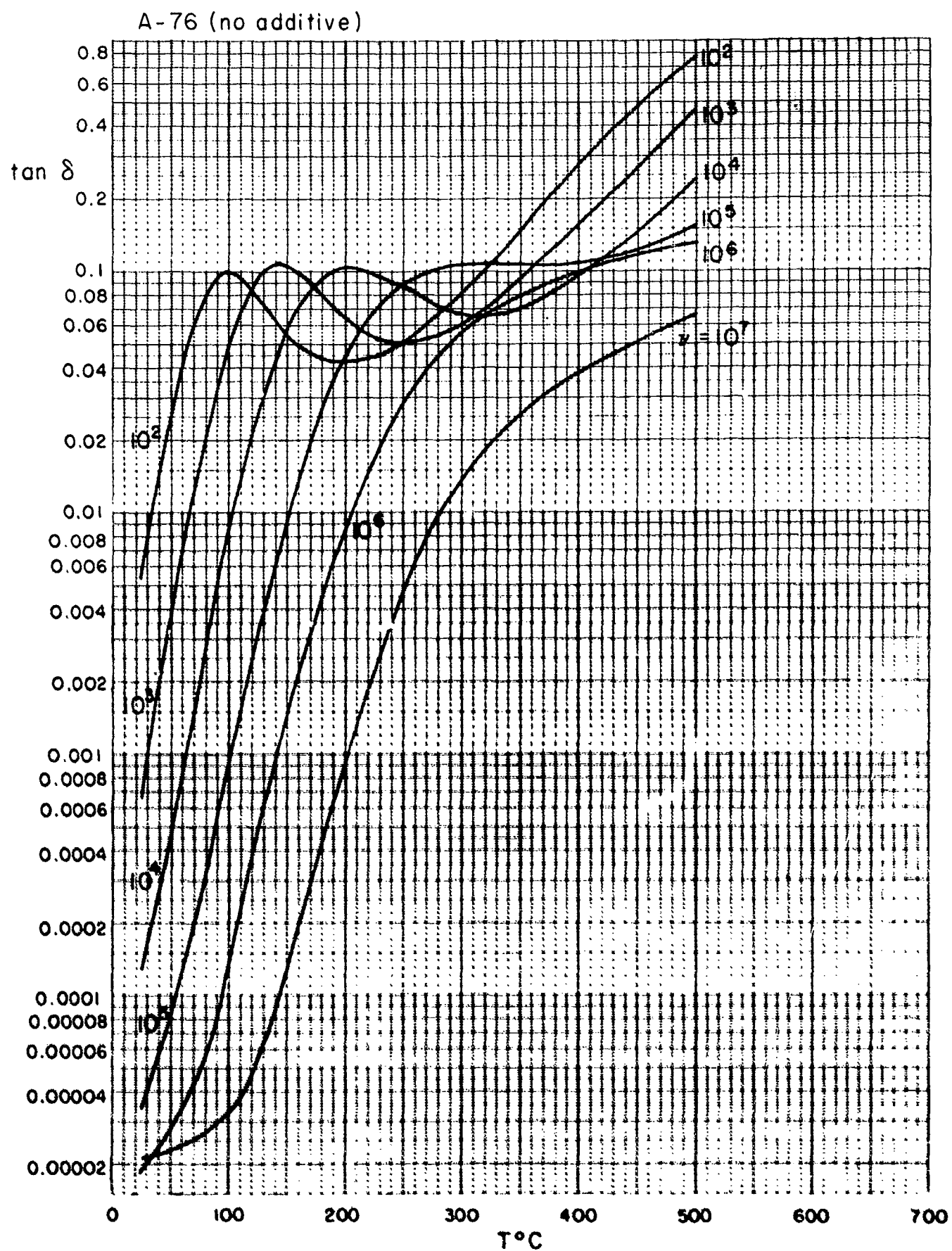
E-20



Alumina, high purity, hot-pressed in C  
Density 3.84 g/cm<sup>3</sup>

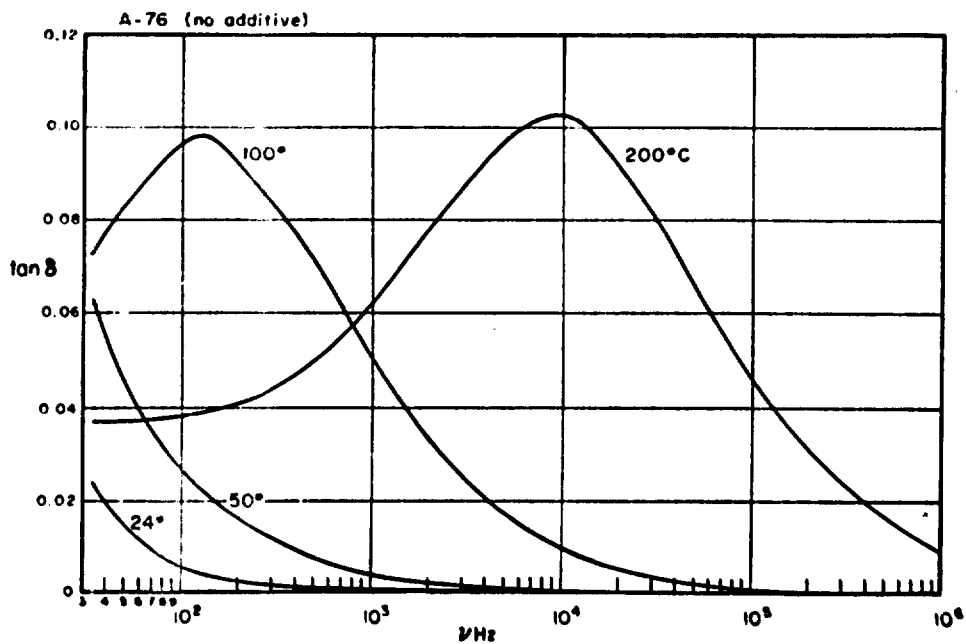
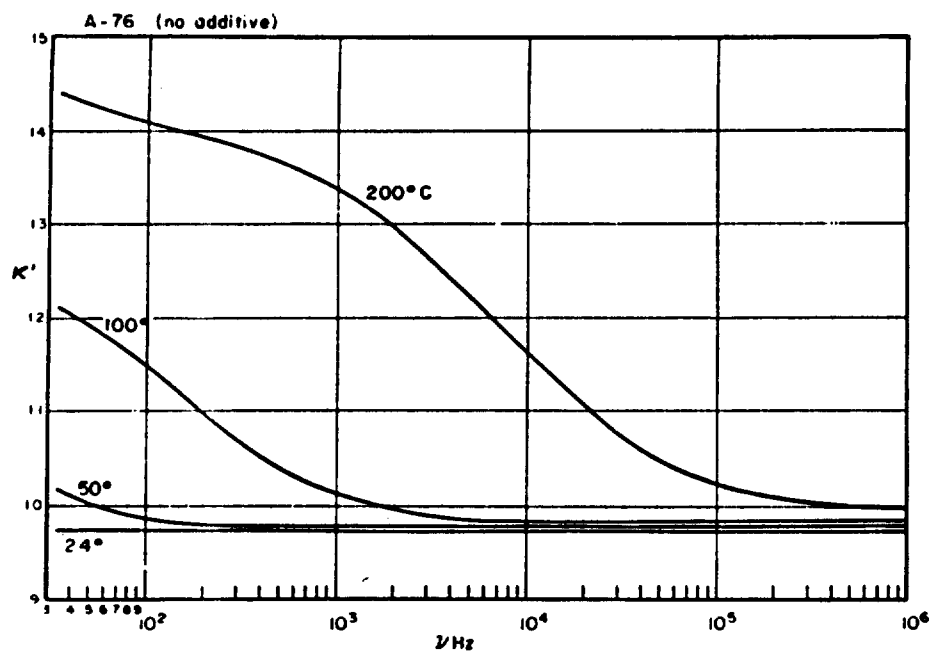
Armour Research Foundation

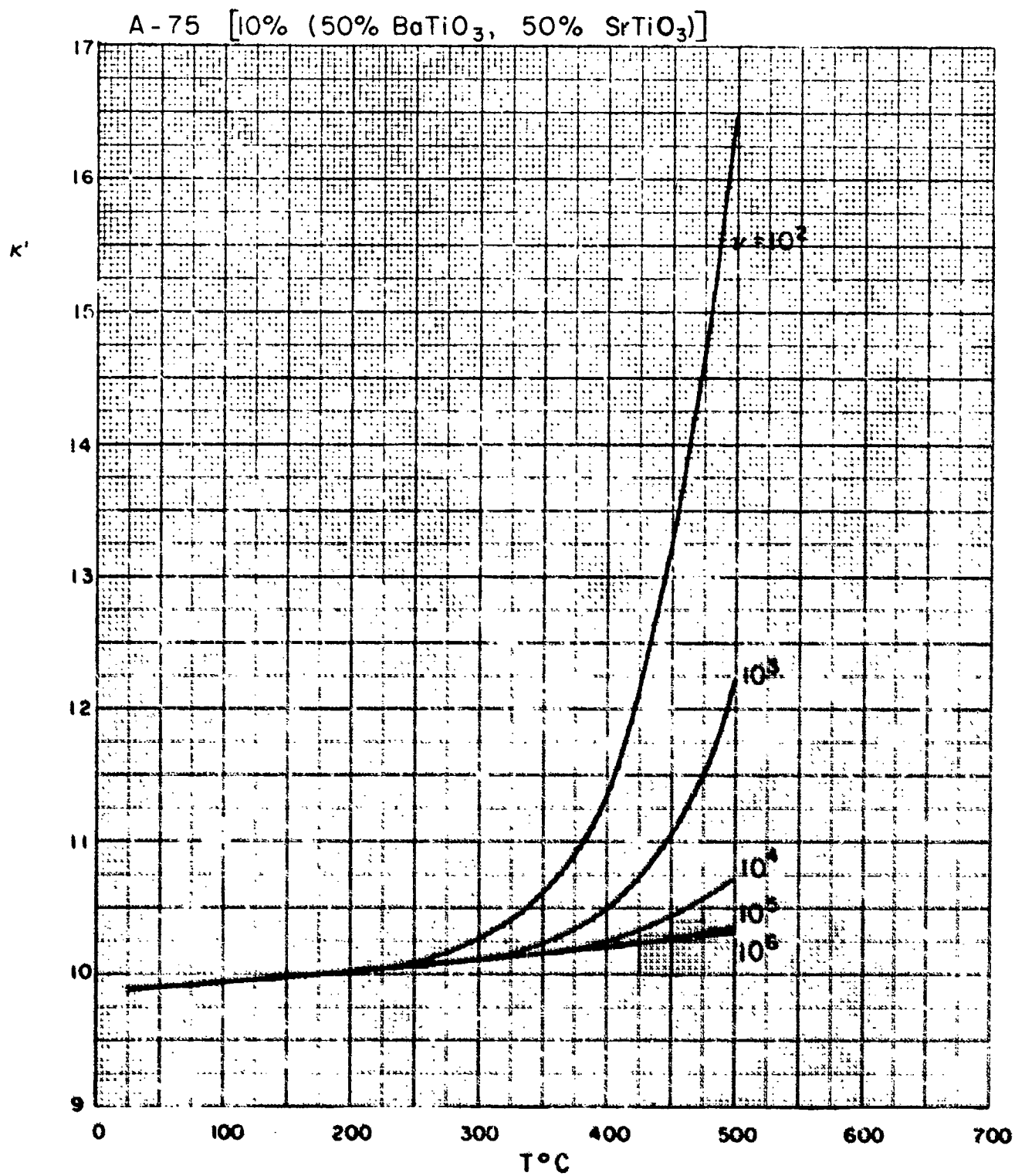




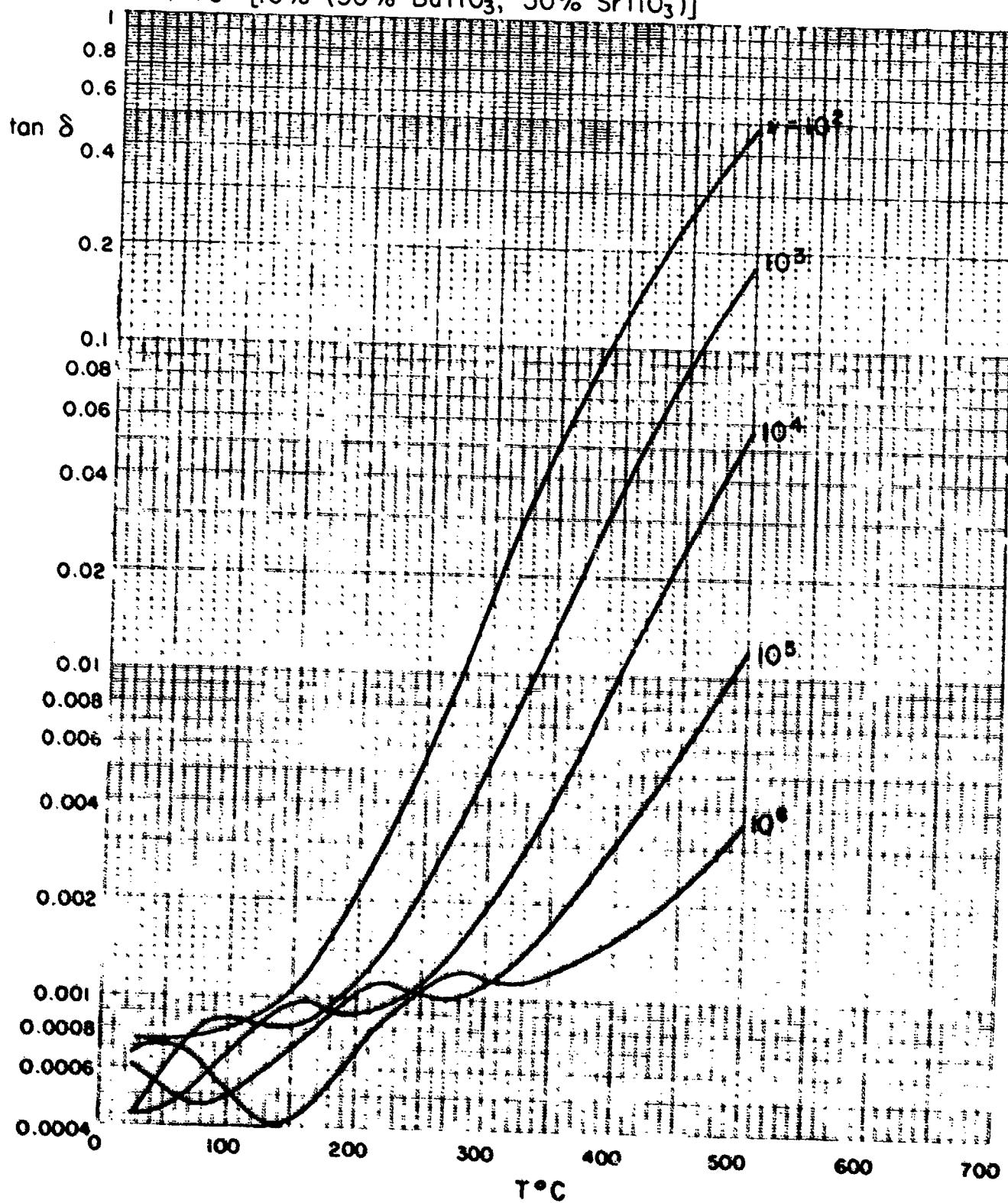
Alumina, hot-pressed,  
in graphite

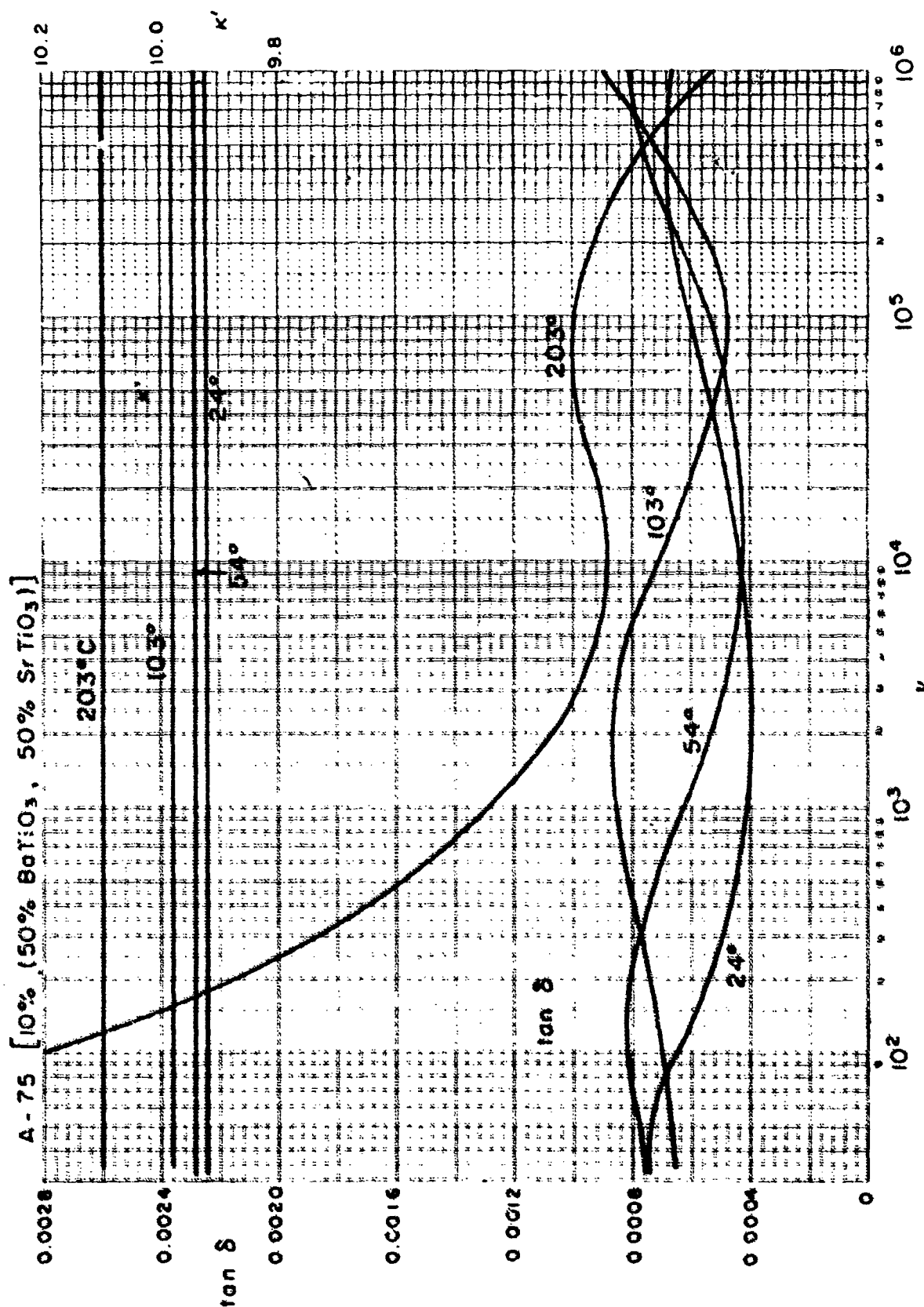
Armour Research Foundation





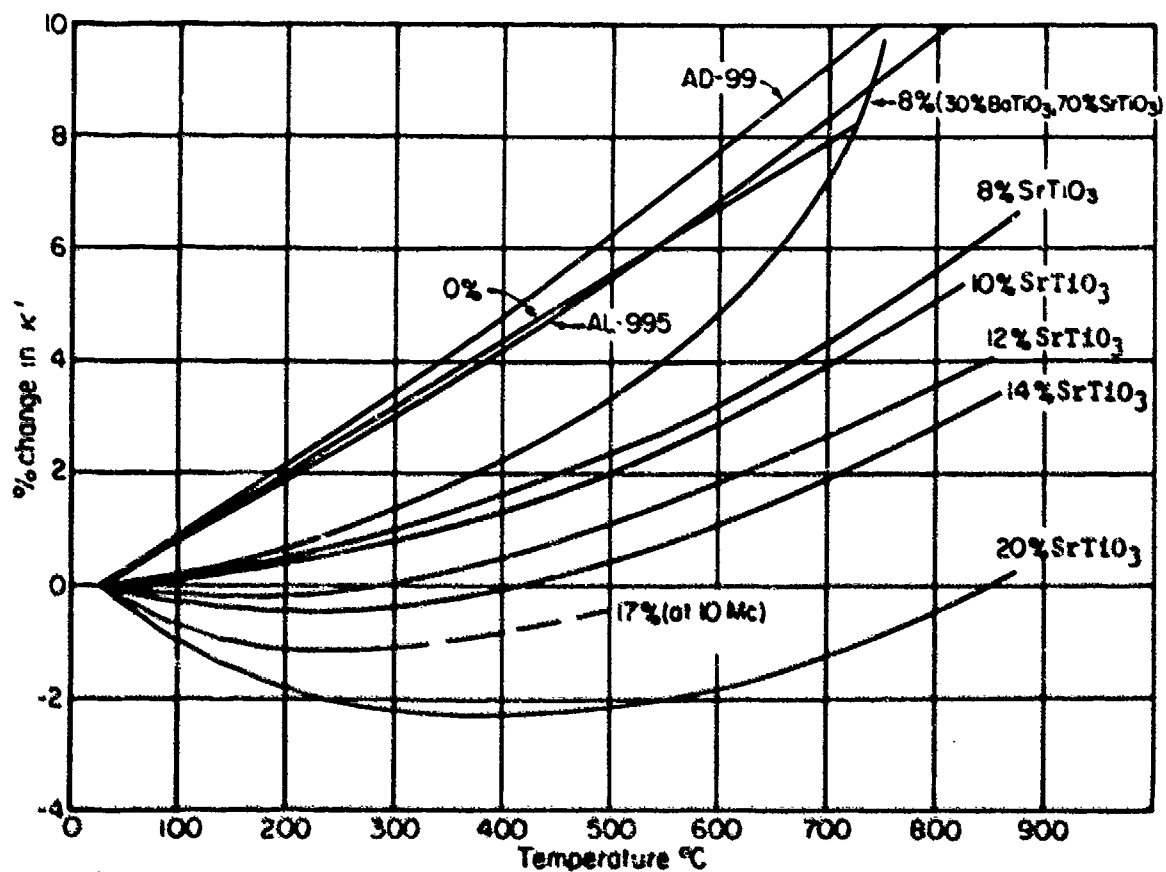
A-75 [10% (50% BaTiO<sub>3</sub>, 50% SrTiO<sub>3</sub>)]



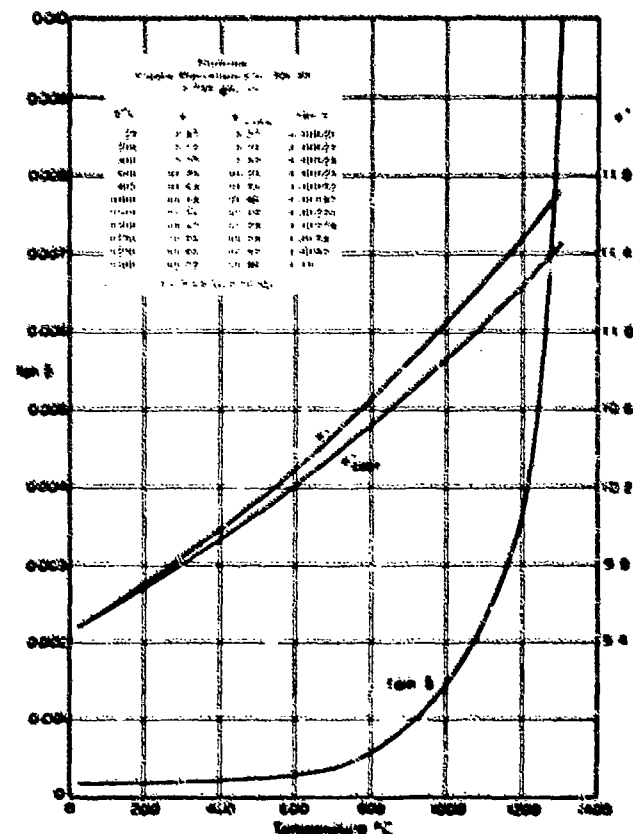
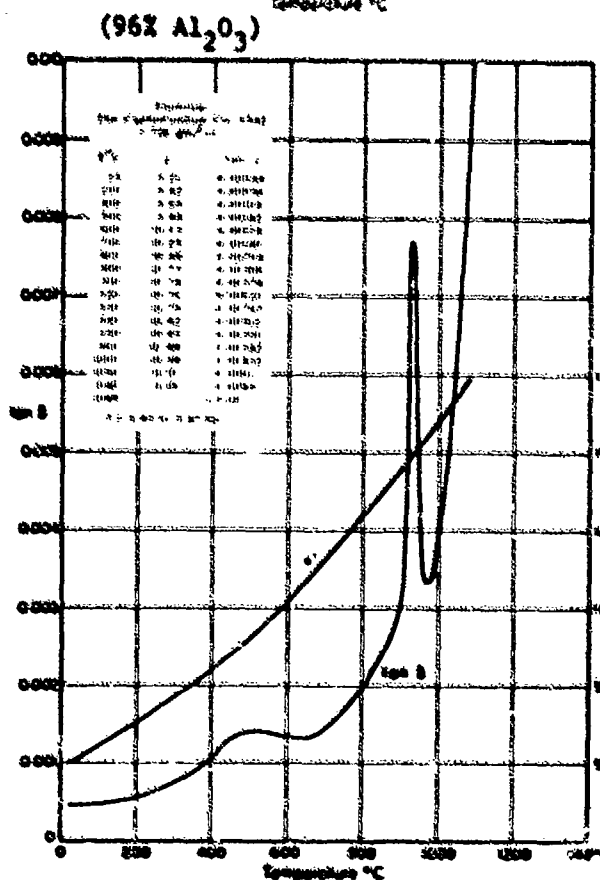
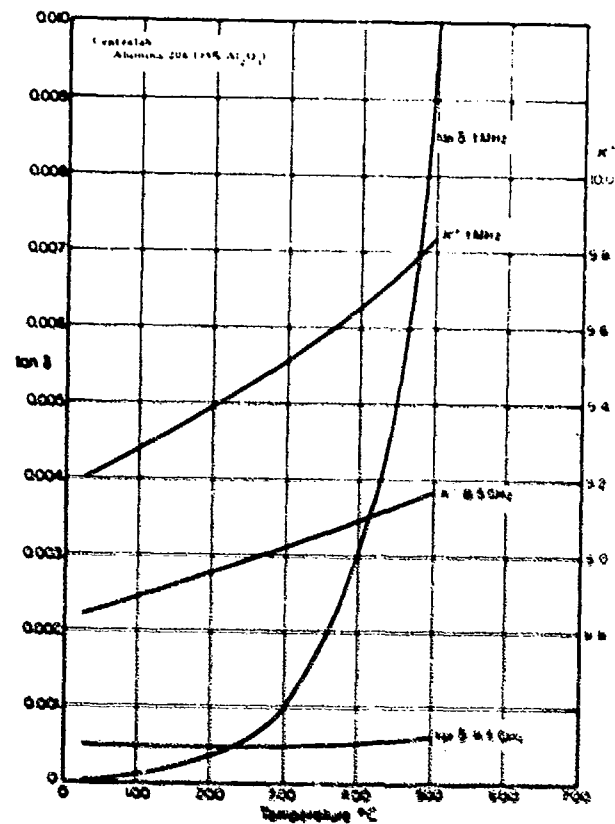
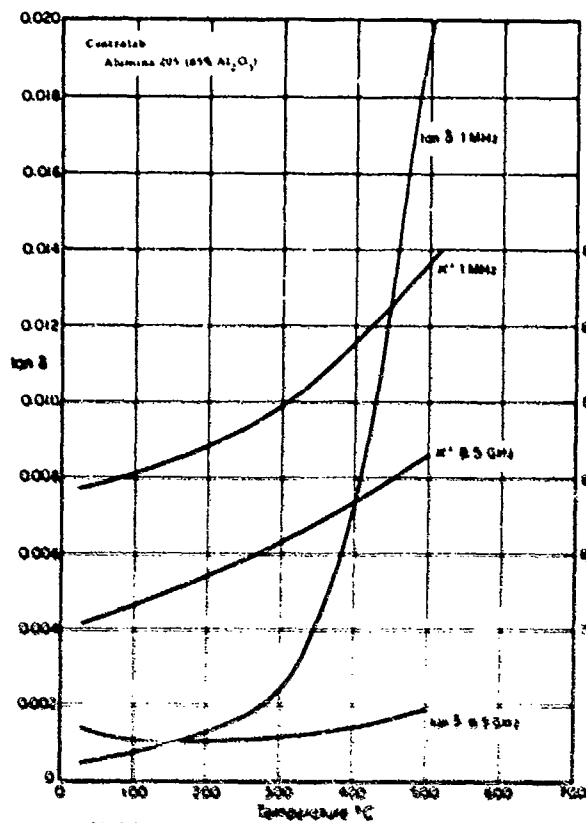




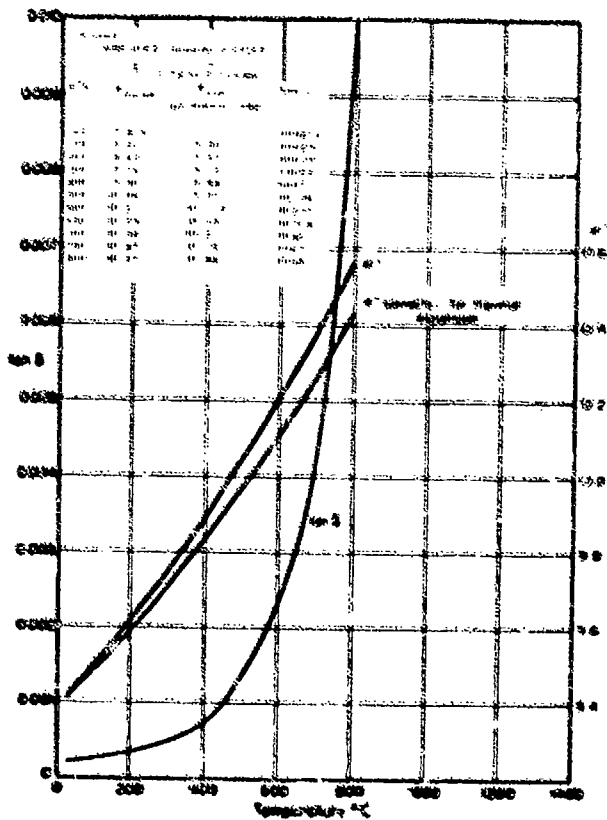
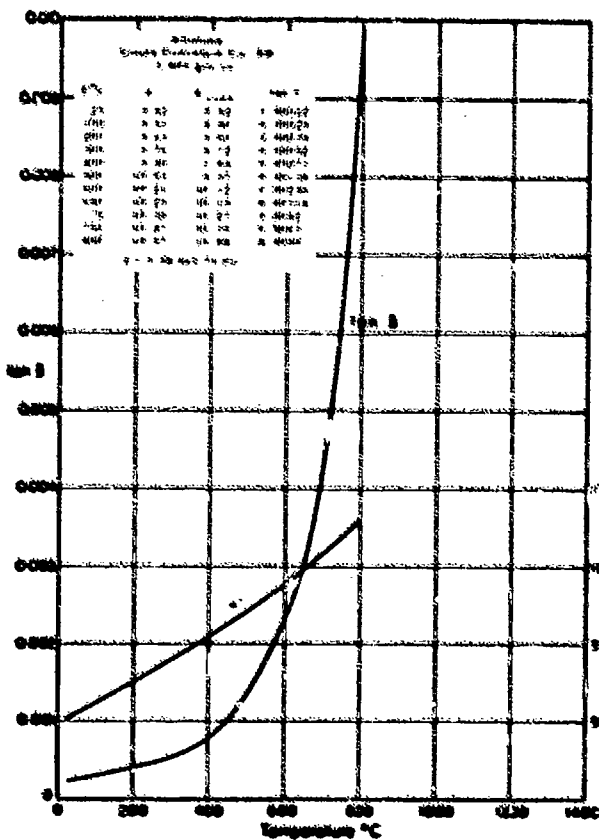
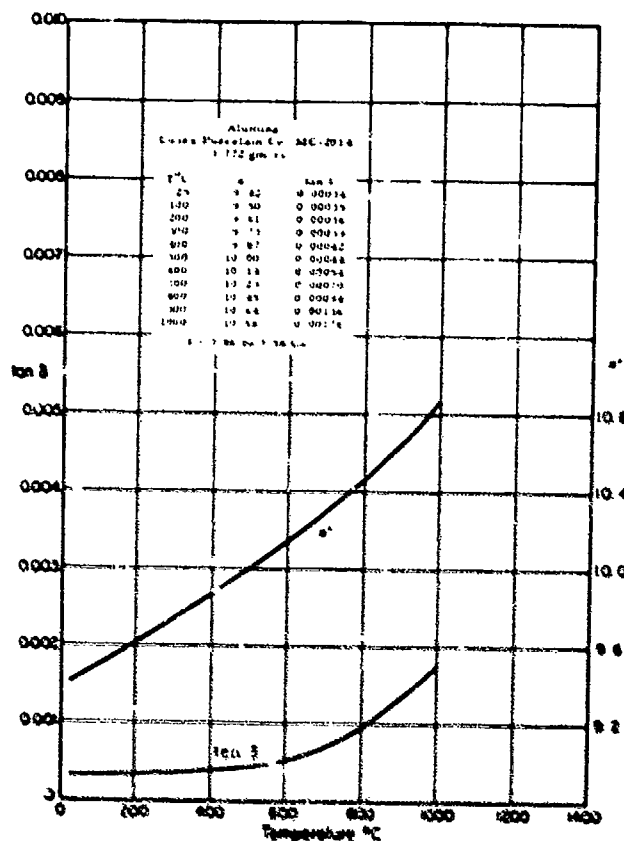
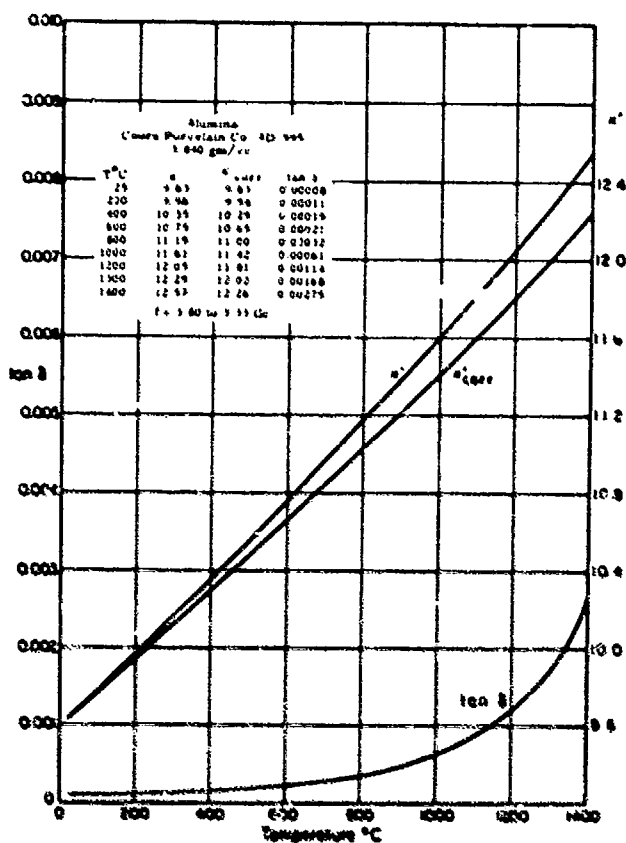
Change in dielectric constant  
with temperature for various  
aluminas at ca. 4000 MHz



# Alumina (cont.)

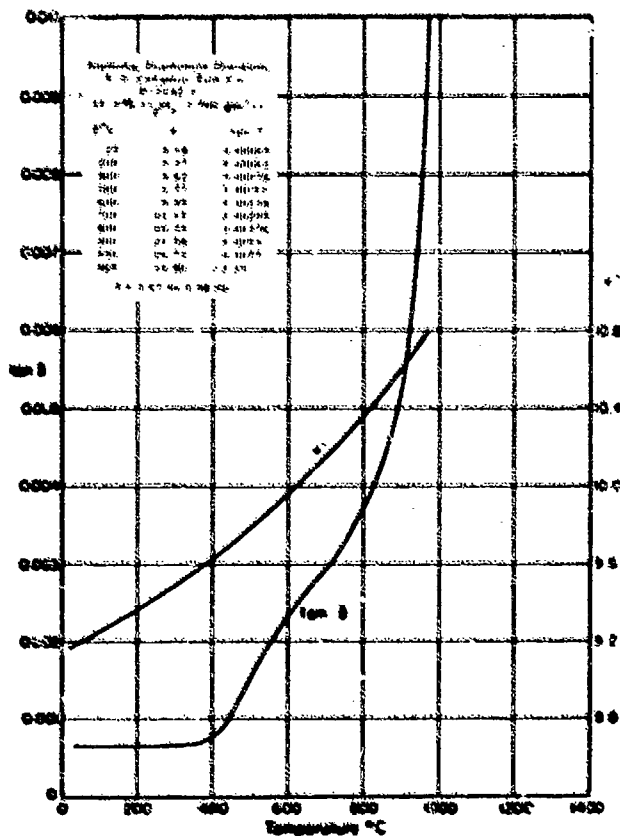
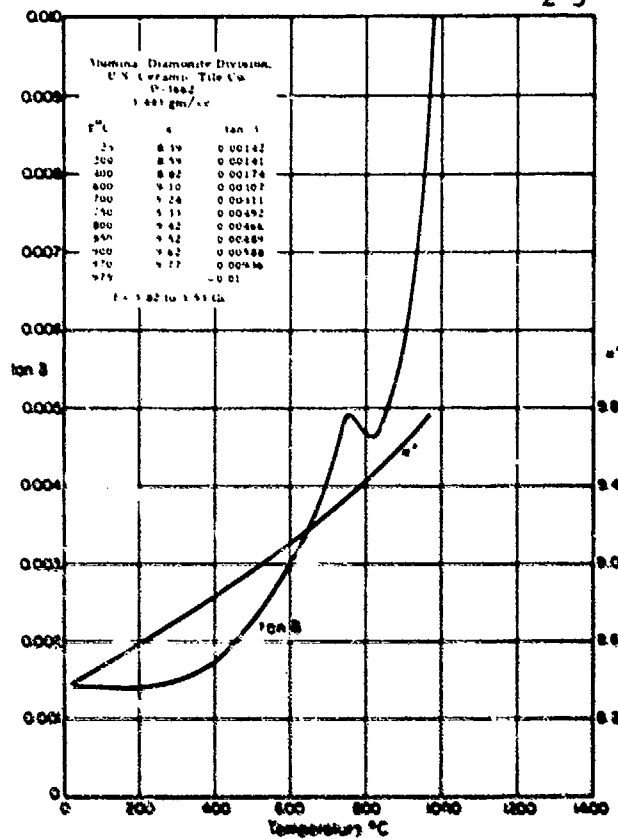
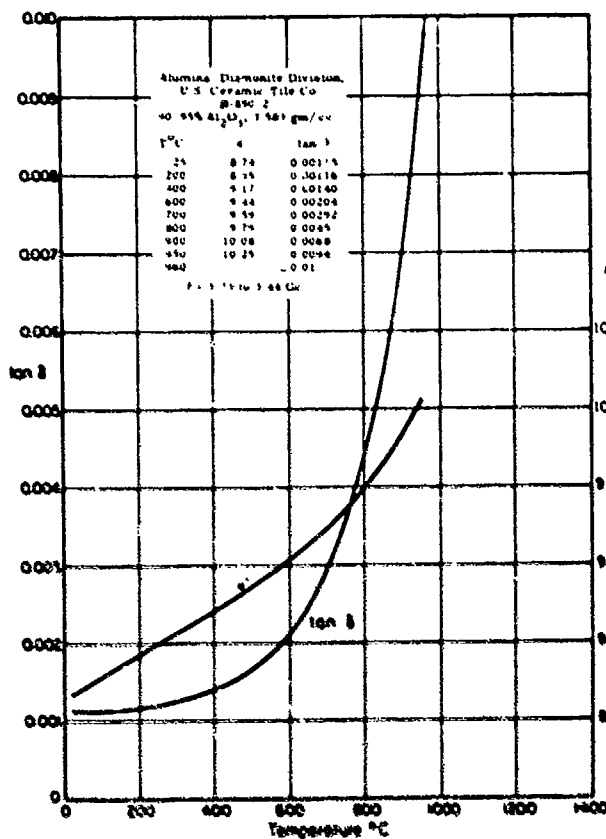


# Alumina (cont.)



# Alumina (cont.)

(85%-90%  $\text{Al}_2\text{O}_3$ )



## Frenchtown 7225

8.52 GHz, 25°C

$\epsilon' = 8.8 \pm 0.05$

$\tan \delta = 0.0013 \pm 0.0002$

on two samples

Aluminum oxide, multicrystalline

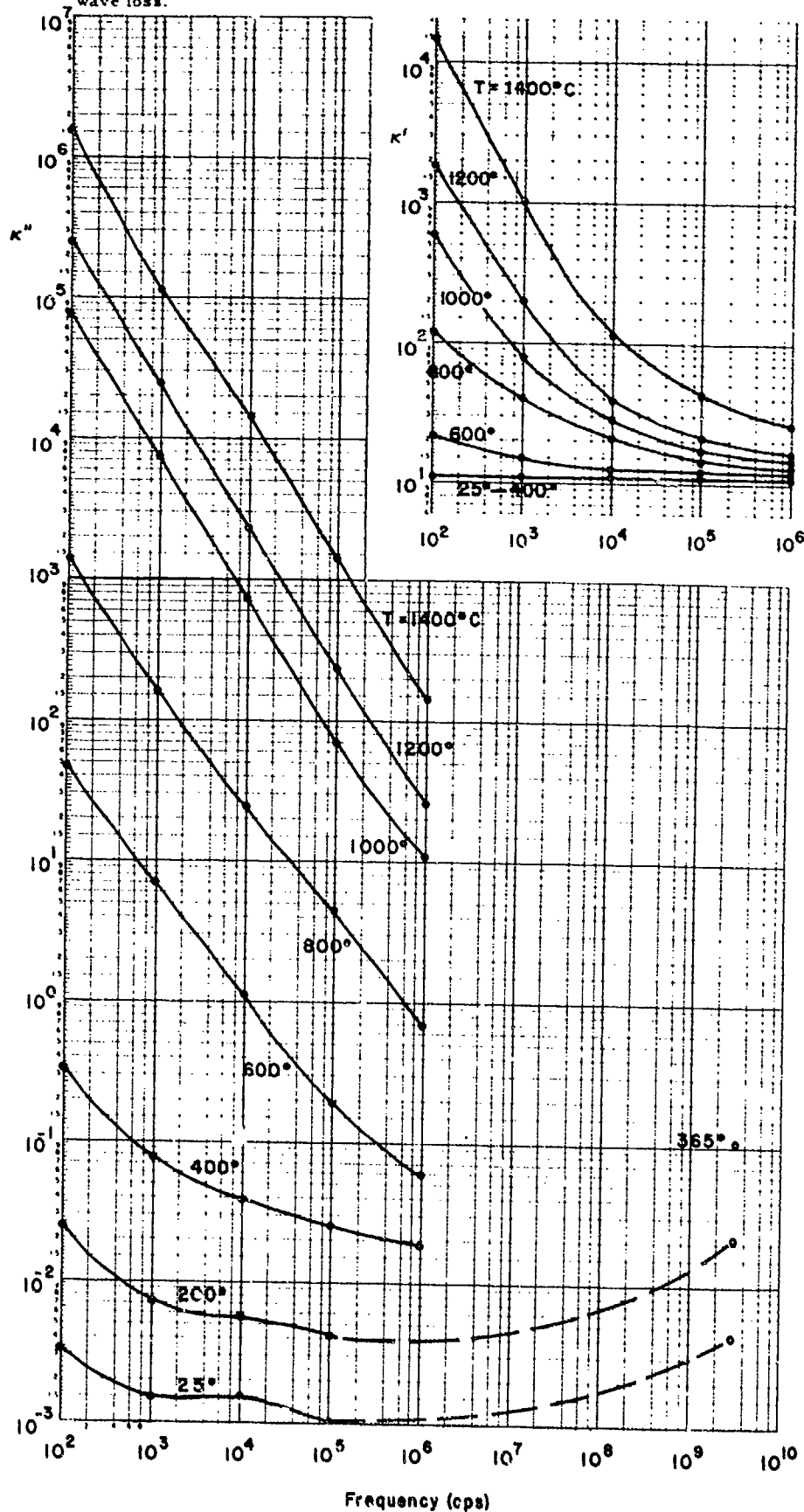
General Electric Company  
Electronic Components Division

AT-100 (near 100%  $\text{Al}_2\text{O}_3$ , fine grained)

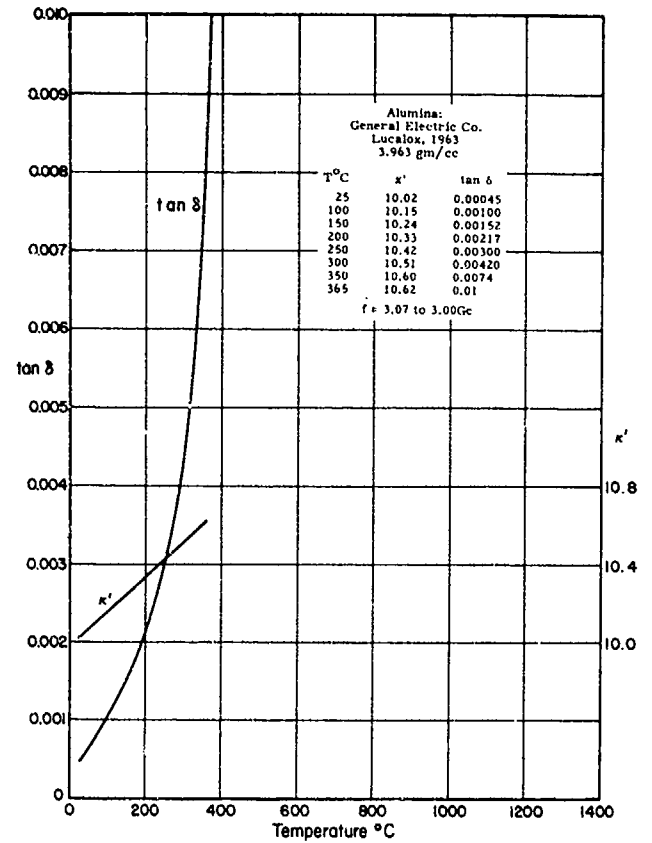
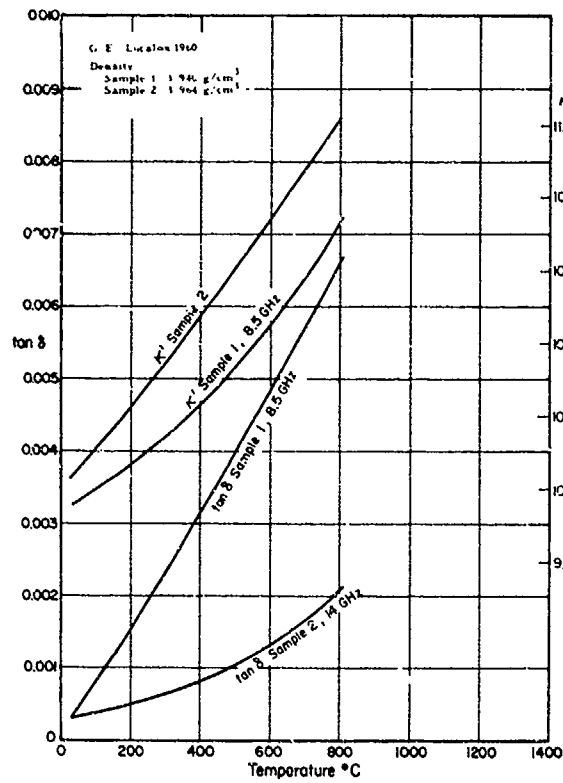
Density,  $\text{g/cm}^3$ : ( $10^2$  to  $10^8$  Hz) - 3.956  
(4; 8 GHz) - 3.955

T°C	Frequency in Hz						$8.5 \times 10^9$
	$10^2$	$10^3$	$10^4$	$10^5$	$10^6$	$10^7$	
25 K	9.98	9.98	9.98	9.98	9.98	9.98	9.96
$10^6 \tan \delta$	7	<1	<1	<1	<1.5	<7	48
100 K	10.09	10.09	10.09	10.09	10.09	10.09	
$10^6 \tan \delta$	52	6	<1	<1	<1.5	<7	
200 K	10.21	10.21	10.21	10.21	10.21	10.21	
$10^6 \tan \delta$	603	128	45	20	10	<7	
300 K	10.42	10.37	10.355	10.35	10.35	10.35	
$10^4 \tan \delta$	61.3	16.3	5.27	2.28	.62	.12	
400 K	10.84	10.68	10.57	10.46	10.44	10.44	
$\tan \delta$	.0307	.0133	.00407	.00103	.00034	.00006	
500 K	12.60	11.28	10.86	10.71	10.63	10.62	
$\tan \delta$	.289	.069	.0237	.0044	.00082	.0002	

$\text{Al}_2\text{O}_3$  ceramic, General Electric Co. "Lucalox." Curves show data on samples bought in 1963. Tabulation of data on earlier samples, 1962, show appreciably lower microwave loss.



# Alumina (cont.)



A-919 (97%  $\text{Al}_2\text{O}_3$ , magnesia-free)

General Electric Co.

Density,  $\text{g/cm}^3$ : ( $10^2$  to  $10^8$  Hz) - 3.747  
( $8.5 \times 10^9$  Hz) - 3.750

		Frequency in Hz						
		$10^2$	$10^3$	$10^4$	$10^5$	$10^6$	$10^7$	$8.5 \times 10^9$
$T^{\circ}\text{C}$								
25	$\kappa$	10.33	9.95	9.62	9.45	9.38	9.37	9.35
	$\tan \delta$	.0240	.0251	.0206	.0082	.00139	.00030	
100	$\kappa$	10.29	9.88	9.60	9.51	9.49	9.49	.00069
	$\tan \delta$	.0316	.0252	.0123	.00303	.00048	.00025	
200	$\kappa$	9.74	9.62	9.60	9.59	9.59	9.59	
	$\tan \delta$	.0210	.0046	.00089	.00021	.00006	<.0001	
300	$\kappa$	10.32	9.89	9.79	9.78	9.77	9.77	
	$\tan \delta$	.0760	.0237	.00475	.00097	.00033	.00010	
400	$\kappa$	14.38	11.13	10.18	9.96	9.90	9.89	
	$\tan \delta$	1.65	.295	.0590	.0106	.00195	.00063	
500	$\kappa$	16.56	13.67	11.44	10.37	10.08	10.03	
	$\tan \delta$		6.83	.866	.122	.0203	.0035	



Aluminum oxide, multicrystalline

A-923 (97%  $\text{Al}_2\text{O}_3$ )

General Electric Company

Density,  $\text{g/cm}^3$ : ( $10^2$  to  $10^8$  Hz) - 3.740  
( $8.5 \times 10^9$  Hz) - 3.740

Frequency in Hz

$T^\circ\text{C}$	$10^2$	$10^3$	$10^4$	$10^5$	$10^6$	$10^7$	$8.5 \times 10^9$
25 $\kappa$	10.26	10.23	10.10	9.61	9.28	9.27	9.24
tan $\delta$	.00227	.00432	.0173	.0357	.00952	.00165	.00067
100 $\kappa$	10.33	10.30	10.19	9.72	9.40	9.39	
tan $\delta$	.00330	.00352	.0178	.0320	.0118	.00157	
200 $\kappa$	10.18	9.73	9.55	9.53	9.50	9.50	
tan $\delta$	.0349	.0238	.0073	.00200	.0089	.00040	
300 $\kappa$	10.38	9.84	9.74	9.65	9.64	9.64	
tan $\delta$	.0678	.0232	.0074	.00313	.00167	.00112	
400 $\kappa$	12.50	10.48	9.97	9.82	9.80	9.79	
tan $\delta$	.205	.082	.0228	.00735	.0035	.0017	
500 $\kappa$	16.72	13.93	10.98	10.08	9.95	9.91	
tan $\delta$	8.03	1.20	.240	.0444	.00976	.0037	

A-923 (97%  $\text{Al}_2\text{O}_3$ )

Density  $3.740 \text{ g/cm}^3$

Freq. 3.74 - 3.37 GHz

$T^\circ\text{C}$	$\kappa$	tan $\delta$	$T^\circ\text{C}$	$\kappa$	tan $\delta$
25	9.31	.00039	705	10.42	.00215
99	9.41	.00042	800	10.63	.00265
184	9.58	.00053	903	10.86	.0033
281	9.72	.00070	973	10.98	.0040
356	9.84	.00090	1025	11.17	.0045
430	9.96	.00112	1050	11.22	.0050
562	10.17	.00160	1109	11.38	.0060
			1132	11.41	.010

## Aluminum oxide, multicrystalline

General Electric Company

A-976 (near 100%)

T°C	Frequency in Hz						8.5 x 10 <sup>9</sup>
	10 <sup>2</sup>	10 <sup>3</sup>	10 <sup>4</sup>	10 <sup>5</sup>	10 <sup>6</sup>	10 <sup>7</sup>	
25    κ	9.90	9.90	9.90	9.90	9.90	9.90	9.81
10 <sup>6</sup> tanδ	70	34	20	10	<10	<10	66
100    κ	10.01	10.01	10.00	10.00	10.00	10.00	
10 <sup>5</sup> tanδ	15	7	3	1.5	<1	<1	
200    κ	10.14	10.12	10.11	10.11	10.11	10.1	
10 <sup>5</sup> tanδ	66	23	8	6	3	<1	
300    κ	10.32	10.29	10.26	10.26	10.26	10.26	
10 <sup>4</sup> tanδ	25	11	3.8	1.1	.4	.2	
400    κ	10.65	10.50	10.43	10.42	10.41	10.41	
10 <sup>4</sup> tanδ	395	102	27.8	8.7	2.9	1.0	
500	11.30	10.81	10.65	10.59	10.58	10.56	
10 <sup>3</sup> tan	461	118	22.4	4.59	1.97	1.1	

Density of disk - 3.919; density of cylinder - 3.917

Aluminum oxide, multicrystalline

A-1000 (99.8%  $\text{Al}_2\text{O}_3$ , fine grained)

General Electric Company

Density,  $\text{g/cm}^3$ : ( $10^2$  to  $10^8$  Hz) - 3.900  
( $8.5 \times 10^9$ ) - 3.896

$T^\circ\text{C}$	Frequency in Hz						
	$10^2$	$10^3$	$10^4$	$10^5$	$10^6$	$10^7$	$8.5 \times 10^9$
25 $\kappa$	10.08	10.08	10.07	10.04	9.98	9.96	9.77
tan $\delta$	.00048	.00048	.00135	.00354	.00664	.00612	.00258
100 $\kappa$	10.20	10.16	10.15	10.15	10.15	10.15	
tan $\delta$	.00184	.00077	.00037	.00058	.00208	.0061	
200 $\kappa$	10.39	10.36	10.33	10.33	10.31	10.29	
tan $\delta$	.00344	.00198	.00101	.00045	.00051	.00170	
300 $\kappa$	10.65	10.55	10.51	10.47	10.45	10.44	
tan $\delta$	.0193	.0059	.00226	.00079	.00049	.00065	
400 $\kappa$	11.86	10.89	10.68	10.63	10.60	10.58	
tan $\delta$	.213	.0461	.00936	.00208	.00076	.00057	
500 $\kappa$	33.3	13.98	11.28	10.83	10.80	10.76	
tan $\delta$	1.212	.585	.130	.0201	.00341	.00135	

## Aluminum oxide, multicrystalline

General Electric Company

A-1004 (94%  $\text{Al}_2\text{O}_3$ )

At 25°C:  $2 \times 10^4$  Hz,  $\kappa = 10.10$ ,  $\tan \delta = .0426$ ;  $5 \times 10^4$  Hz,  $\kappa = 9.76$ ,  $\tan \delta = .0536$ ;  
 $3 \times 10^5$ ,  $\kappa = 9.19$ ,  $\tan \delta = .0341$ .

Density, g/cm<sup>3</sup>: ( $10^2$  to  $10^8$  Hz) - 3.645( $8.5 \times 10^9$  Hz) - 3.649

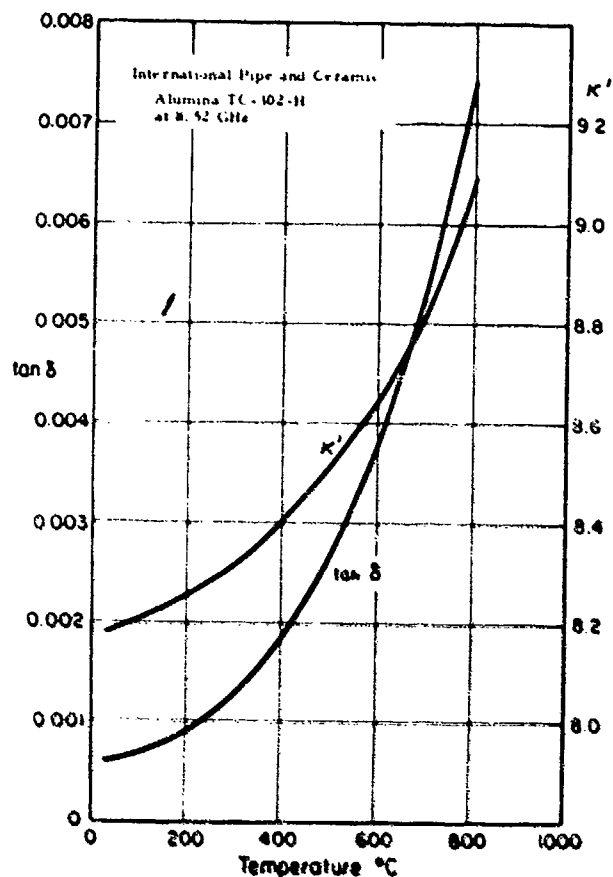
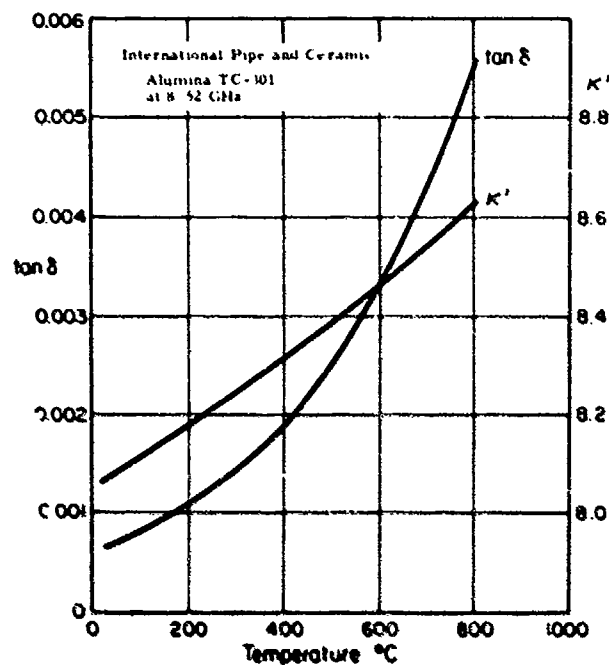
## Frequency in Hz

T°C	$10^2$	$10^3$	$10^4$	$10^5$	$10^6$	$10^7$	$8.5 \times 10^9$
25 $\kappa$	10.48	10.41	10.26	9.51	9.10	9.00	9.01
tan $\delta$	.00226	.00716	.0319	.0534	.0142	.00228	.00125
100 $\kappa$	10.63	10.55	10.48	9.89	9.19	9.10	
tan $\delta$	.00355	.00555	.0208	.0505	.0271	.0515	
200 $\kappa$	10.49	9.73	9.34	9.25	9.21	9.20	
tan $\delta$	.0450	.0439	.0171	.0047	.00163	.00105	
300 $\kappa$	10.52	9.81	9.55	9.44	9.37	9.36	
tan $\delta$	.0767	.043	.0132	.0059	.0022	.0020	
400 $\kappa$	12.63	10.39	9.78	9.54	9.43	9.36	
tan $\delta$	.227	.0887	.033	.0136	.0072	.0040	
500 $\kappa$	19.19	12.59	10.55	10.03	9.83	9.74	
tan $\delta$	1.16	.452	.121	.0298	.0133	.0071	

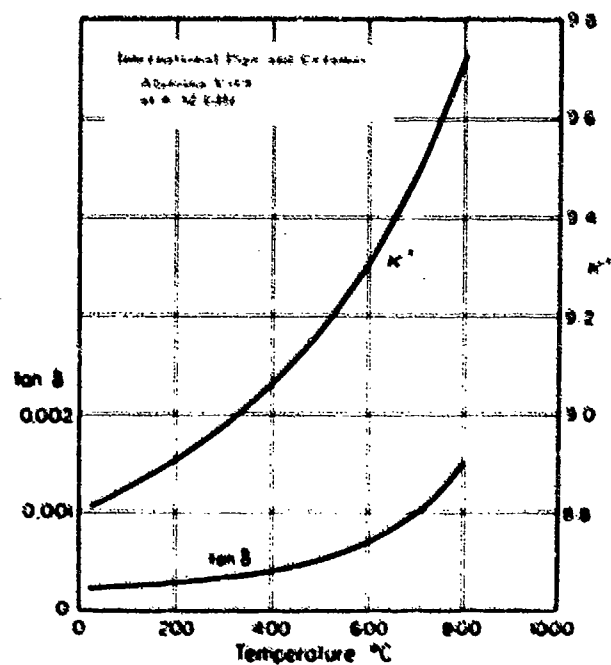
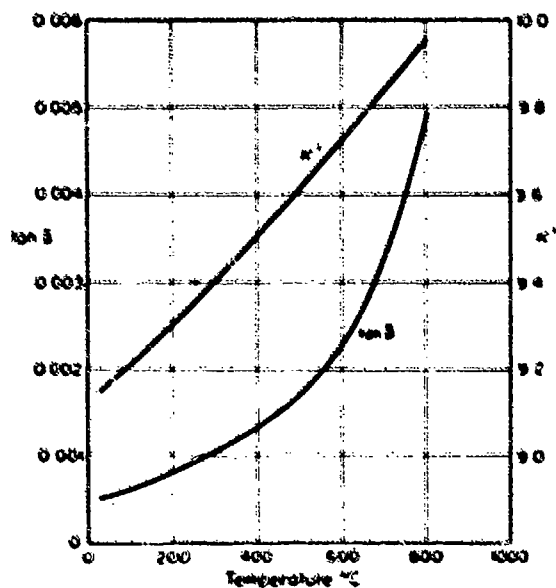
A-1004 (94%  $\text{Al}_2\text{O}_3$ ), density 3.649 g/cm<sup>3</sup>

## Freq. 1.80 - 3.61 GHz

T°C	$\kappa$	tan $\delta$
25	9.02	.00076
100	9.11	.00078
200	9.26	.00081
300	9.40	.00093
400	9.55	.00109
500	9.69	.00128
600	9.84	.00177
650	9.92	.00335
700	10.00	.0093



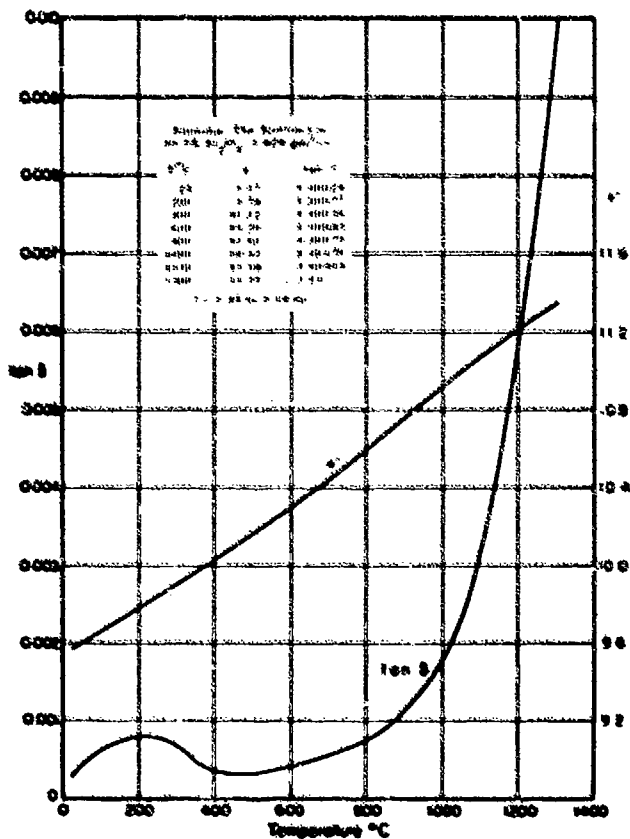
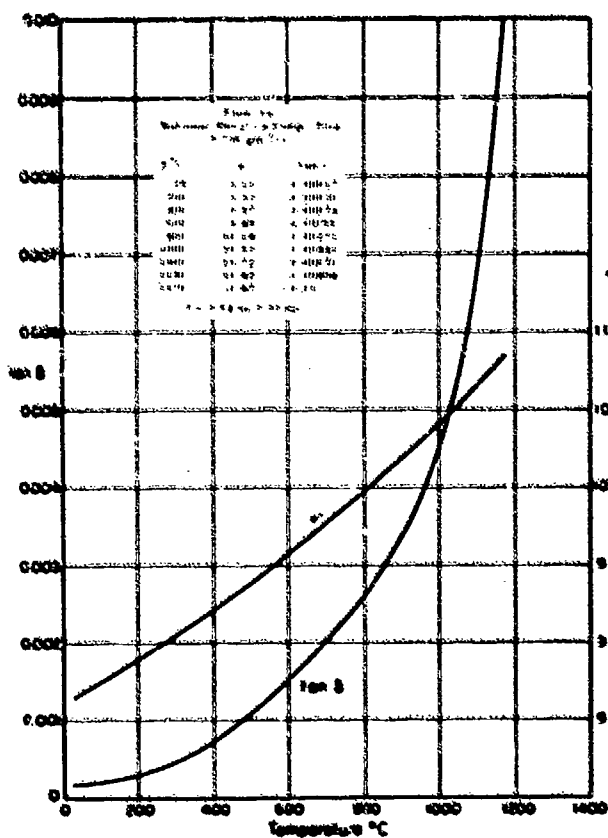
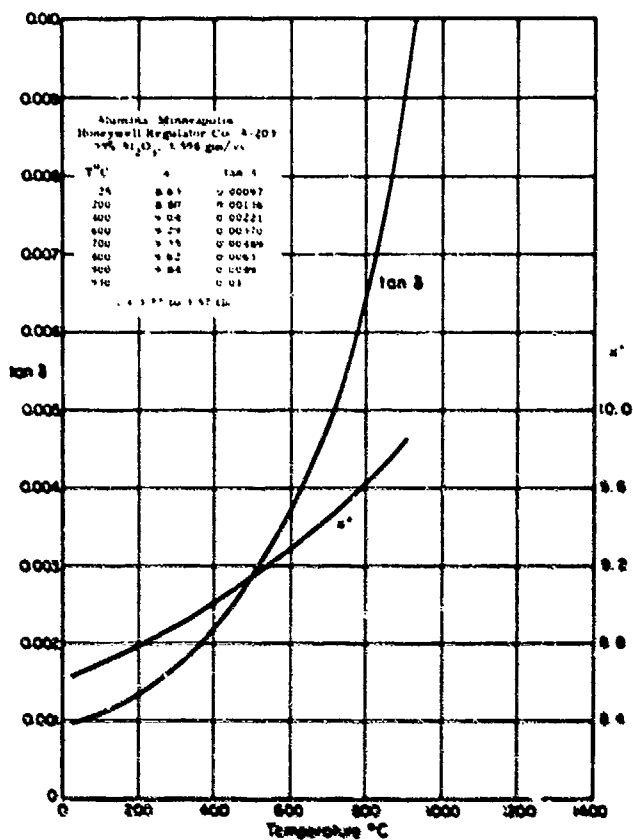
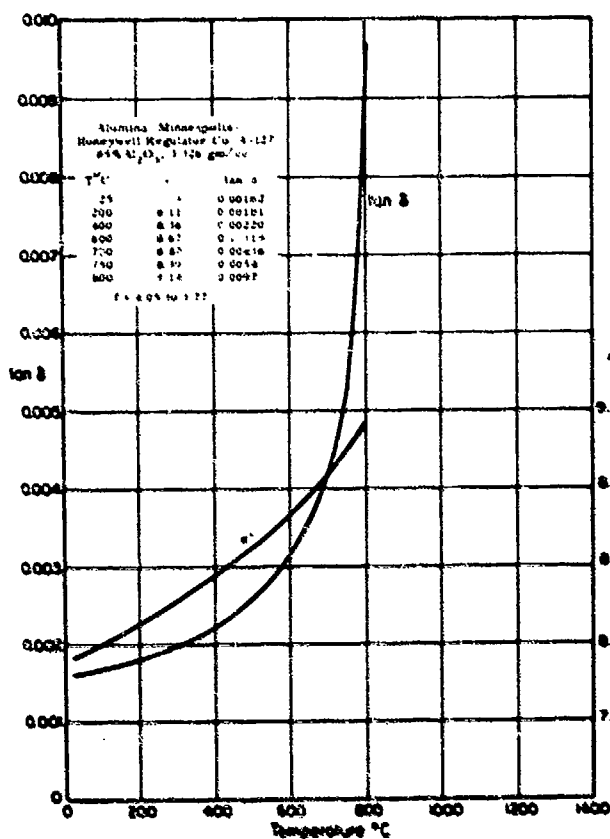
International Pipe and Ceramic  
TC-351, at 8.52 GHz



High-purity alumina at 50 GHz, 25°C  
 $\kappa' = 9.5$ ,  $\tan \delta = 1 \times 10^{-5}$

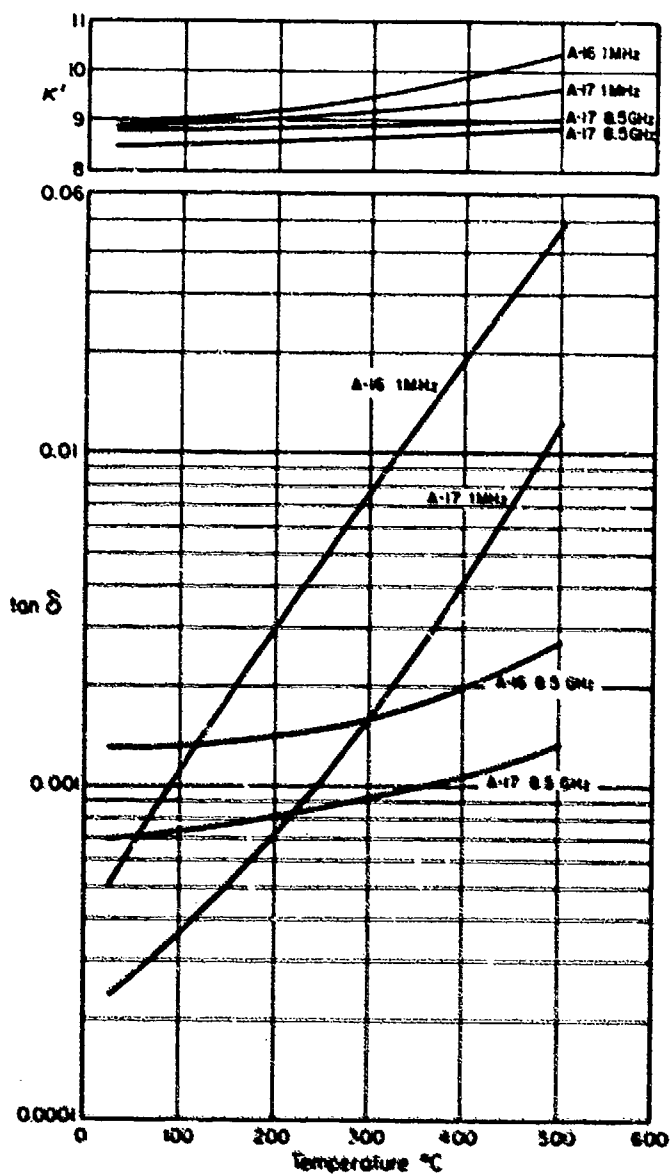
Kearfott

# Alumina (cont.)

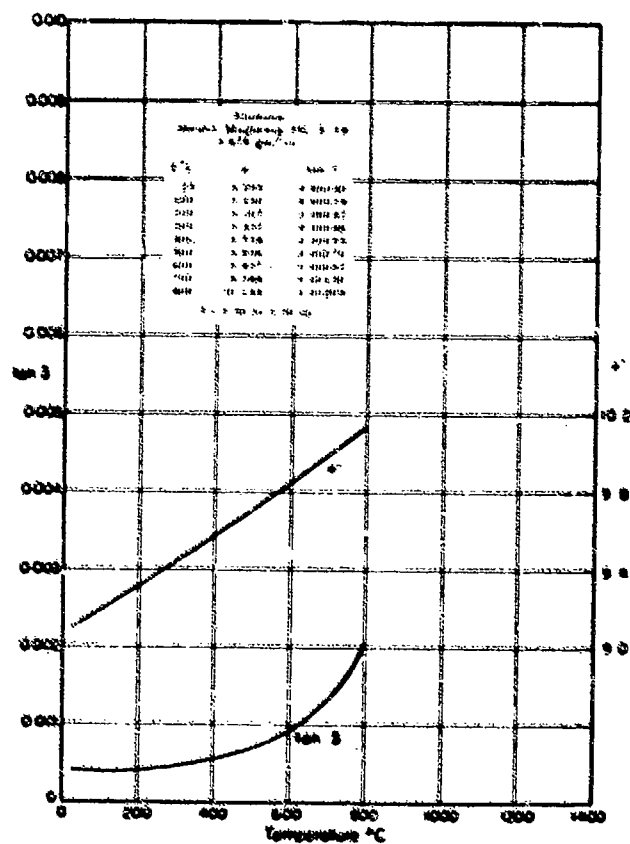


# Alumina (cont.)

Aluminum oxide, multicrystal, 1959  
Raytheon Company

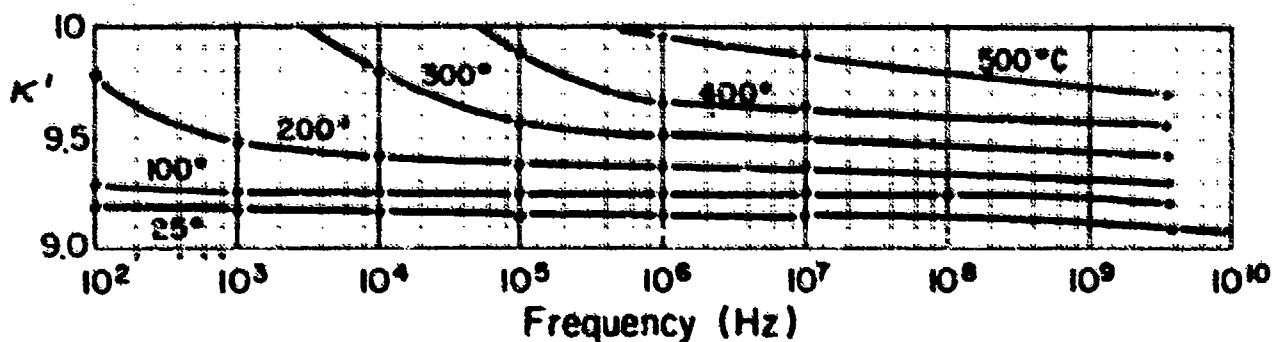
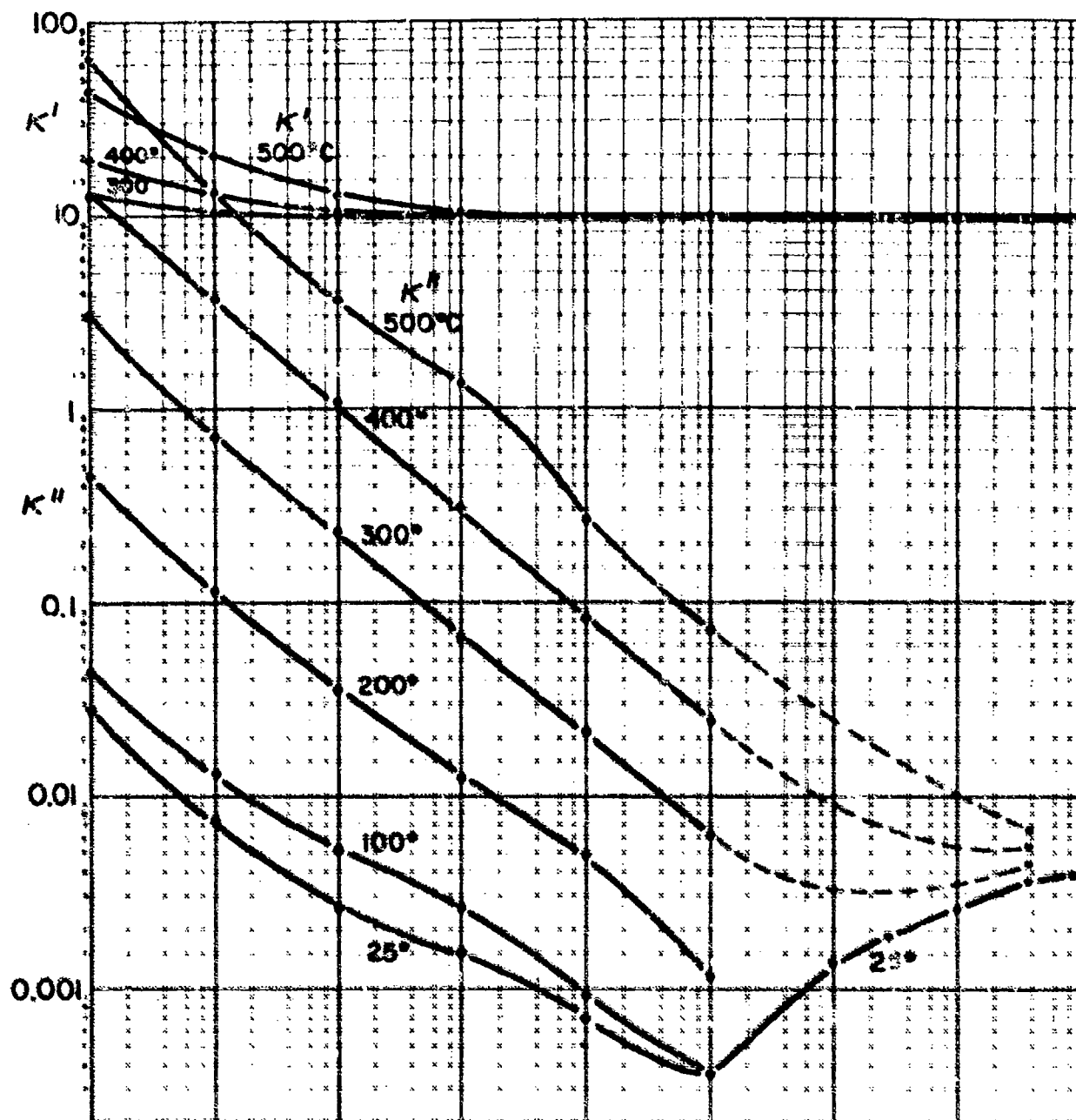


# Steatit-Magnesia A.G.



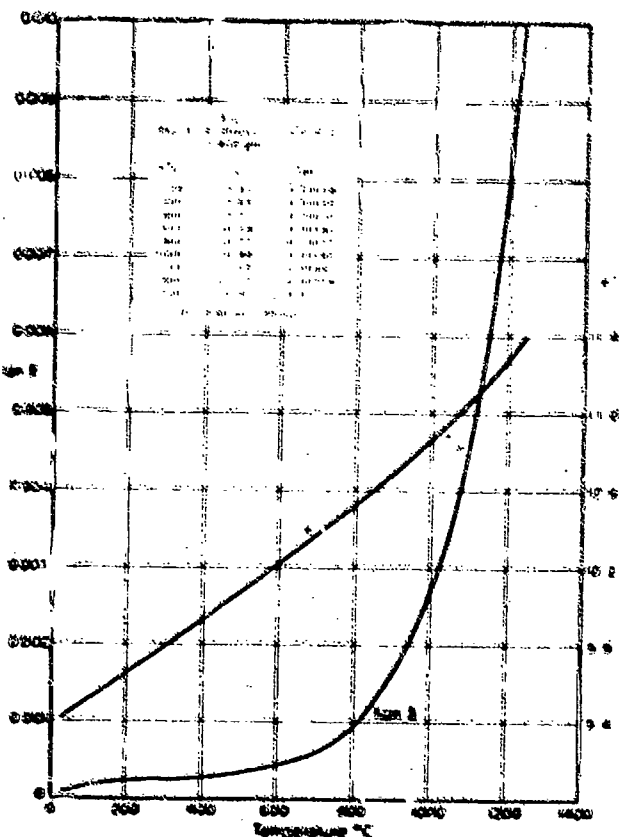
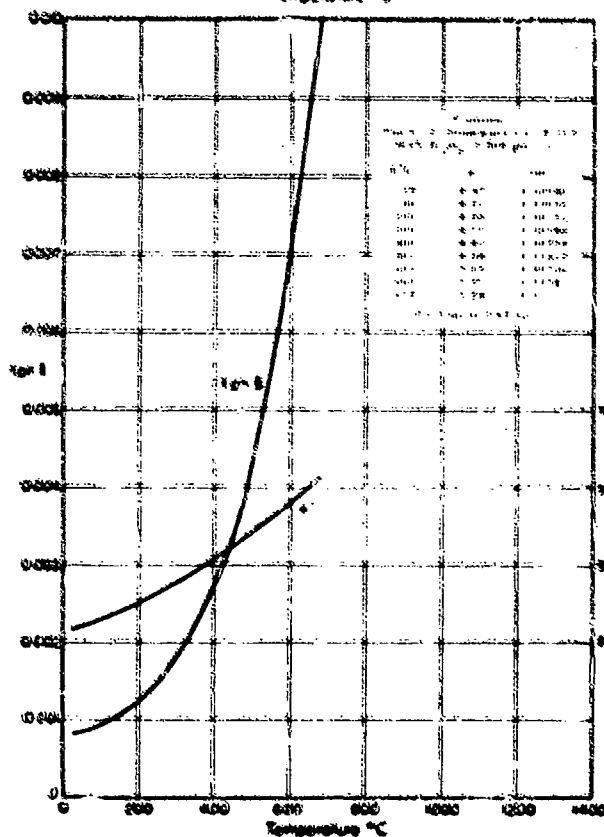
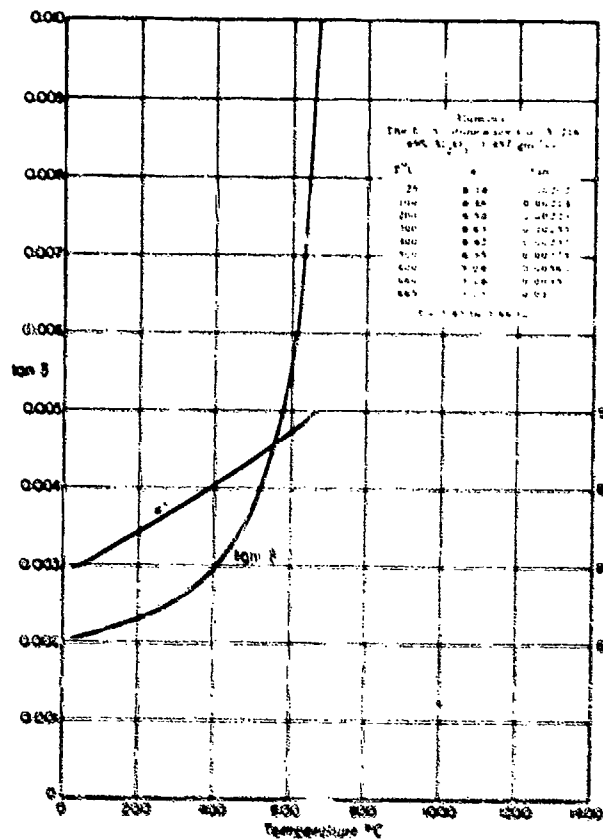
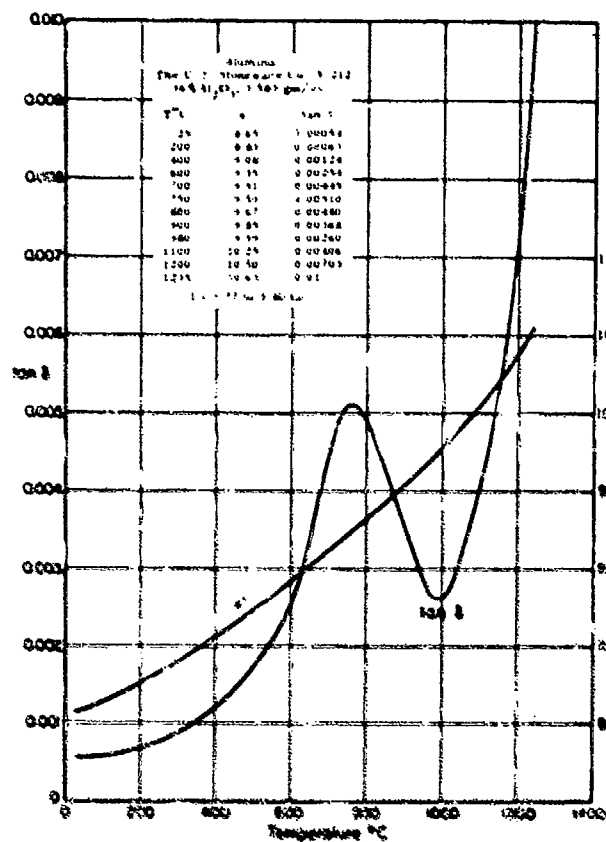
Aluminum oxide A-18  
(multicrystalline)  
Density 3.676 g/cm<sup>3</sup>

Steatit-Magnesia Aktiengesellschaft

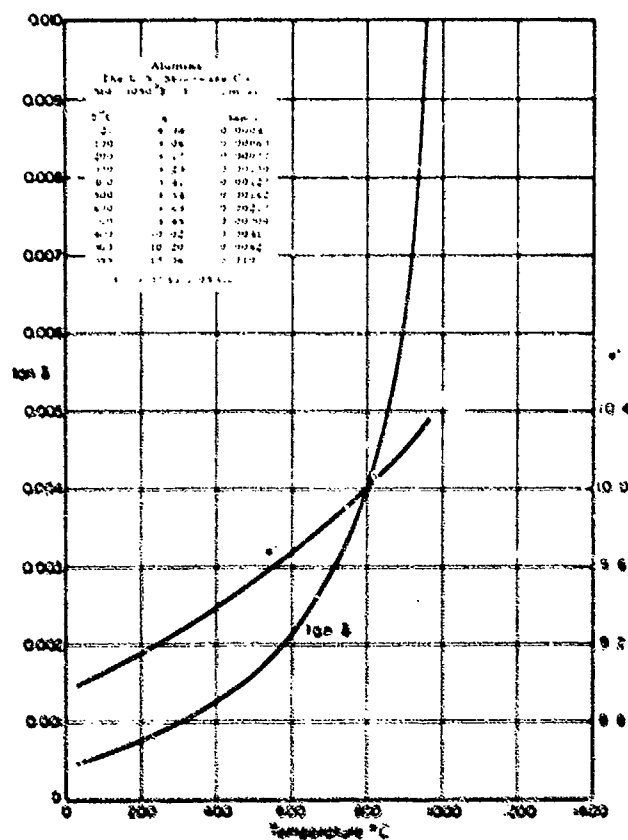


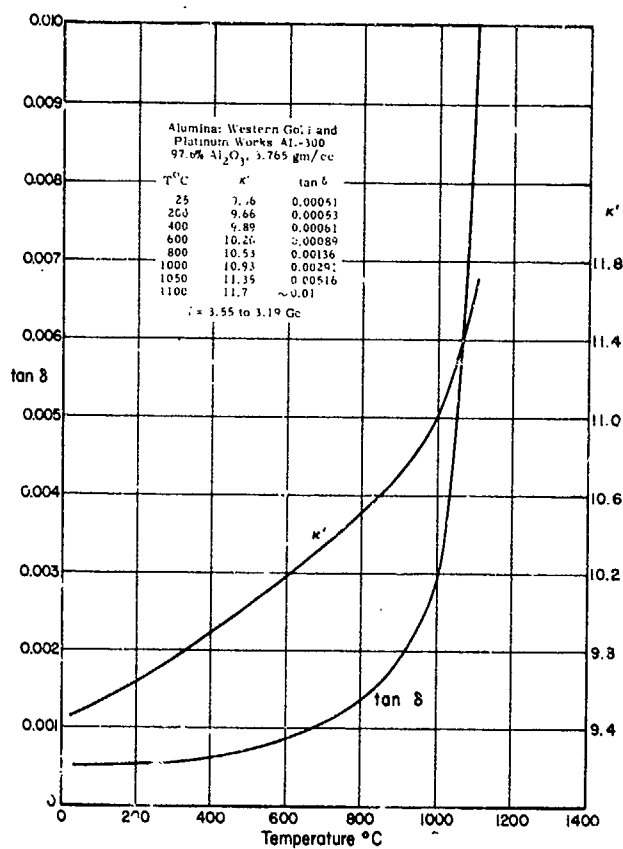


# Alumina (cont.)



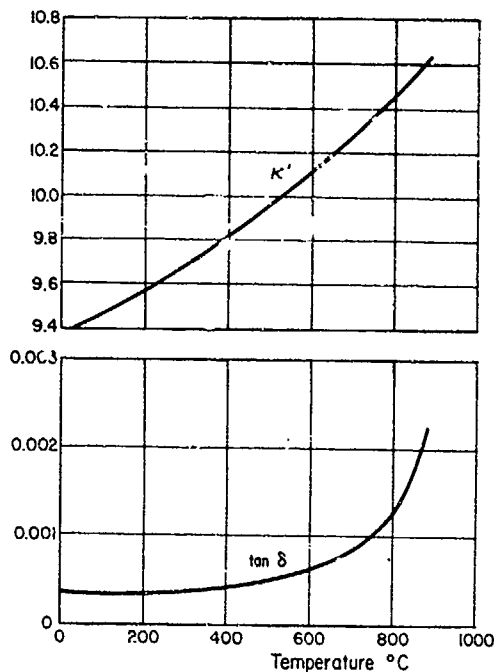
## Alumina (cont.)





# Alumina: Western Gold and Platinum

AL-300 modified  
Density 3.771 g/cm<sup>3</sup>  
4.1 to 3.85 GHz

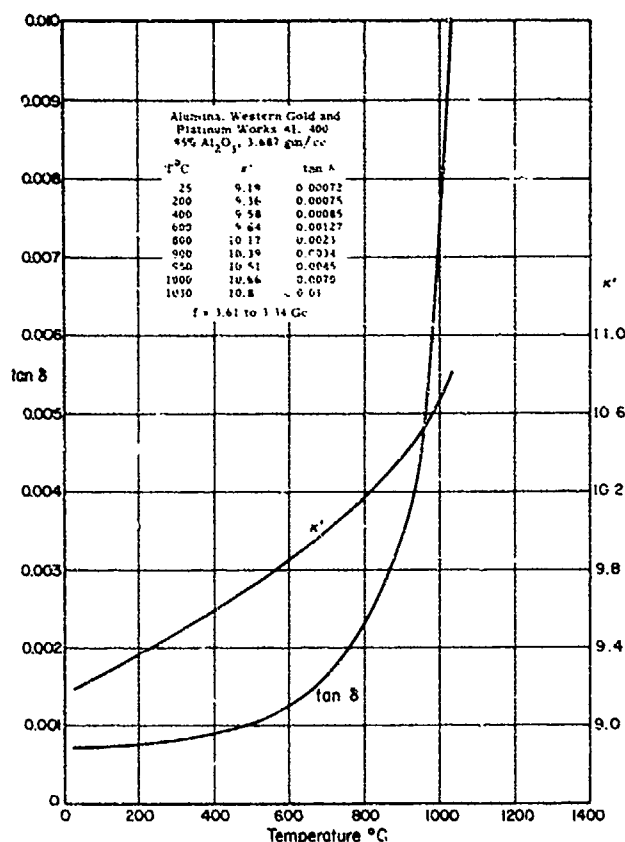


T °C	κ'	tan δ
25	9.39	.00037
122	9.48	.00037
185	9.55	.00038
258	9.63	.00038
339	9.74	.00041
393	9.79	.00045
500	9.95	.00055
572	10.08	.00064
788	10.43	.00120
881	10.63	.00219

At 25°C

f (Hz)	κ'	tan δ
10 <sup>7</sup>	9.44	.00012
10 <sup>9</sup>	9.40	.00035
3 × 10 <sup>9</sup>	9.39	.00037
8.5 × 10 <sup>9</sup>	9.38	.00046

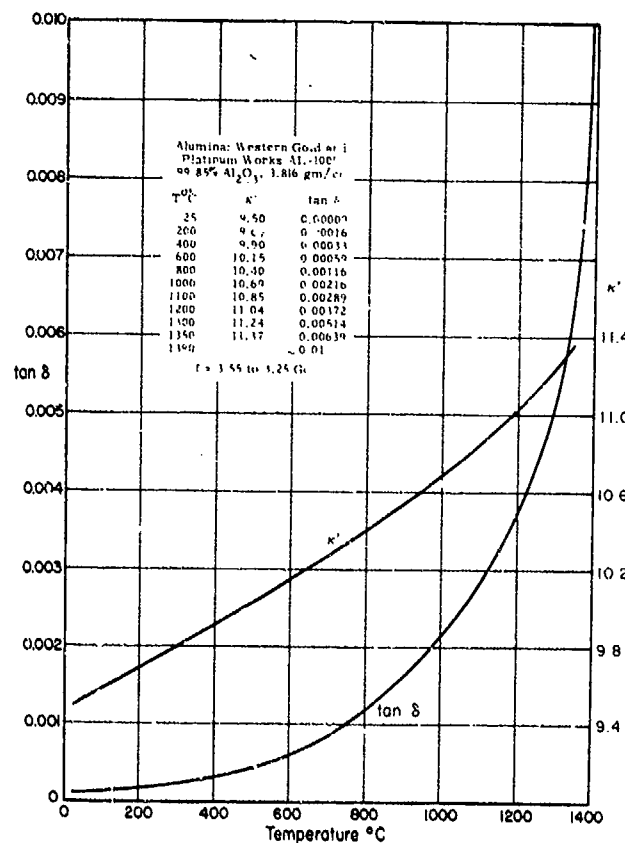
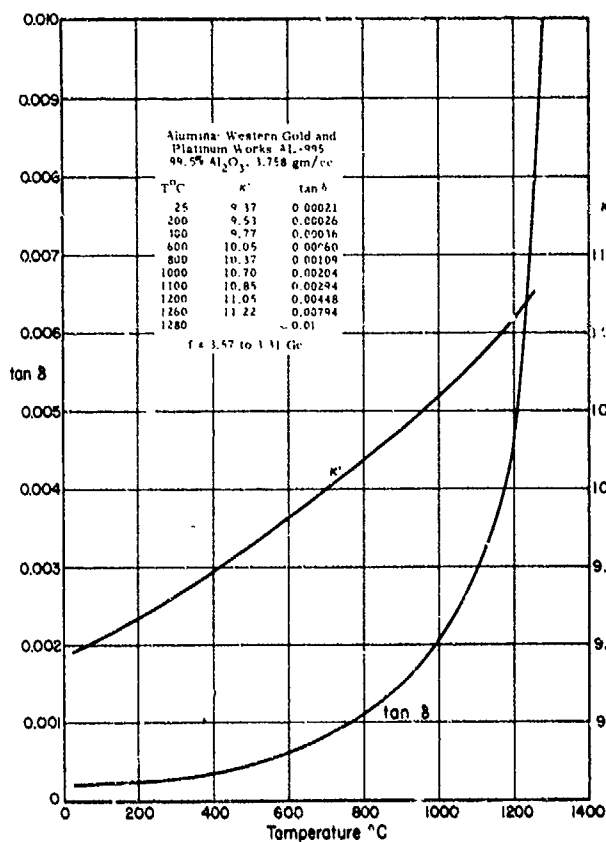
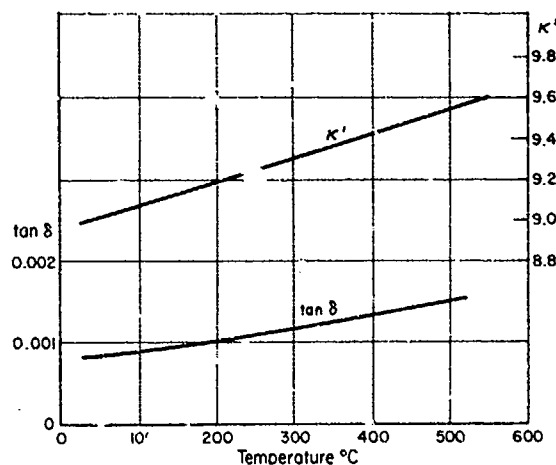
# Alumina (cont.)



# Aluminum oxide, AL-500 Western Gold and Platinum (multicrystalline) Density 3.665 g/cm<sup>3</sup>

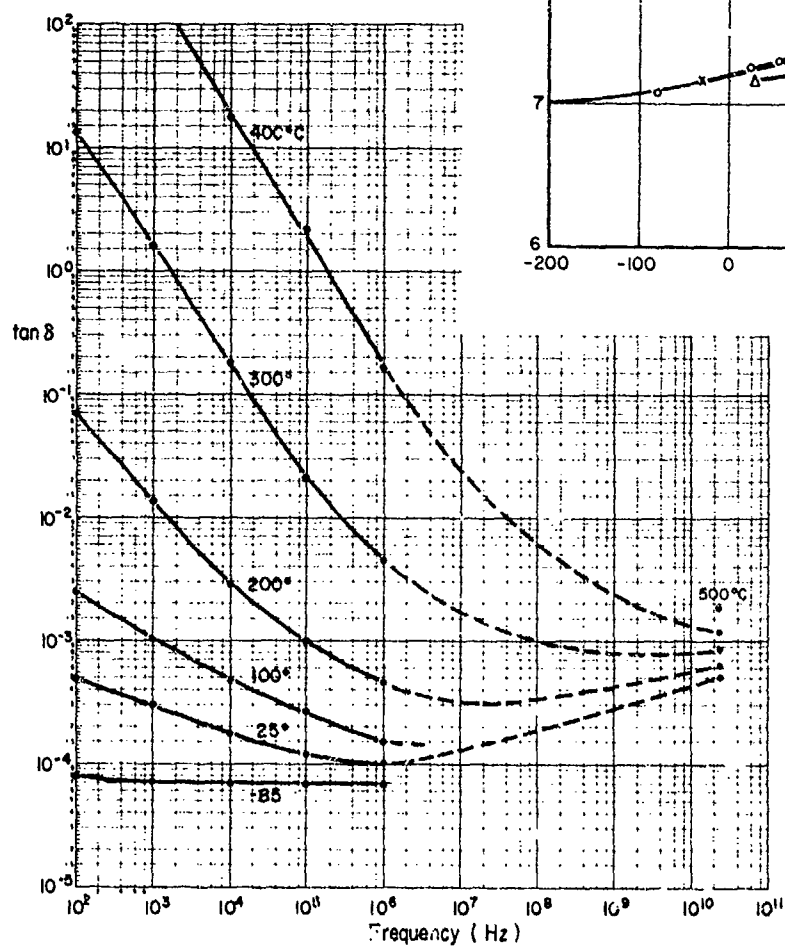
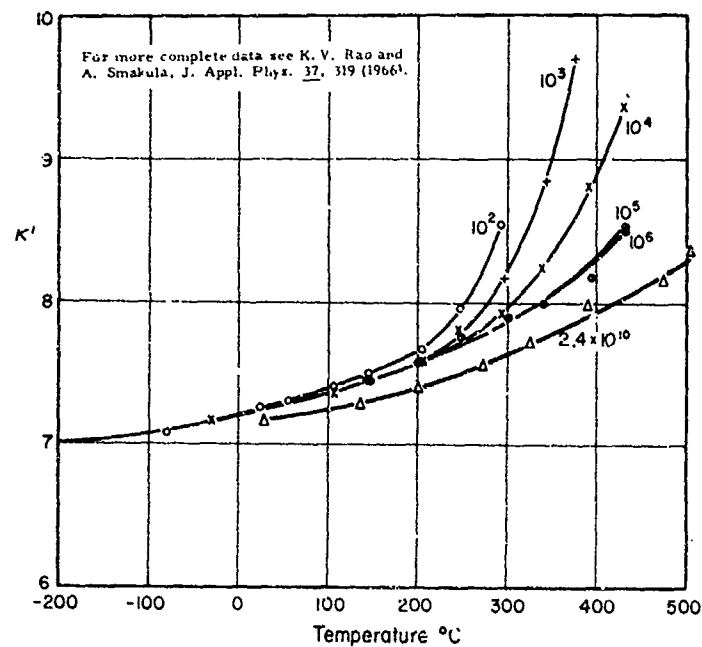
At 25°C

f (Hz)	K'	tan δ
10 <sup>7</sup>	9.07	.00026
10 <sup>9</sup>	9.03	.00062
3x10 <sup>9</sup>	9.02	.00070
8.5x10 <sup>9</sup>	see the graph below	



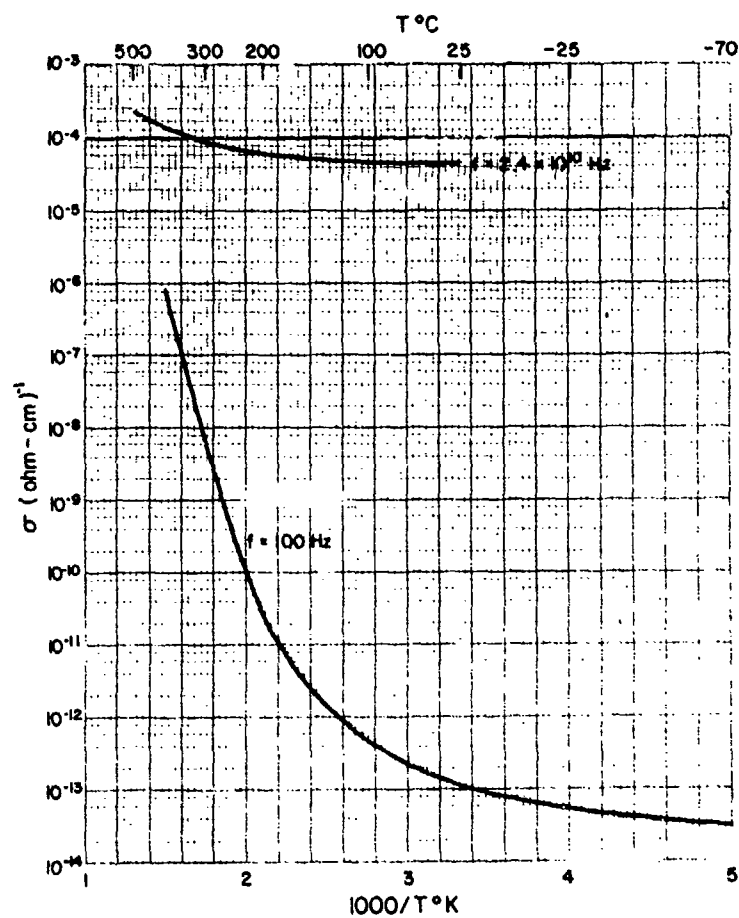
Barium fluoride  
Single crystal

Massachusetts Institute of Technology  
Crystal Physics Laboratory



Barium fluoride (cont)  
Single Crystal

Massachusetts Institute of Technology  
Crystal Physics Laboratory



Beryllium oxide  
BeO crystal KSC 7011A  
Electronic Space Products Inc.

$E \parallel c$  axis  
 $10^2$  to  $10^7$  Hz  
 $\kappa' = 7.41 \pm 0.1$   
 $\tan \delta < 0.0006$

# Beryllium oxide (cont.)

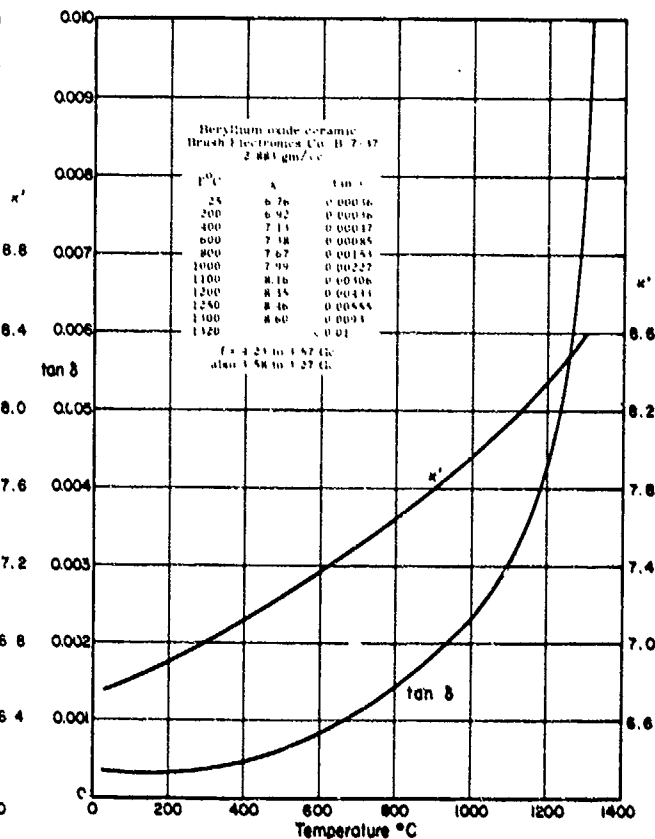
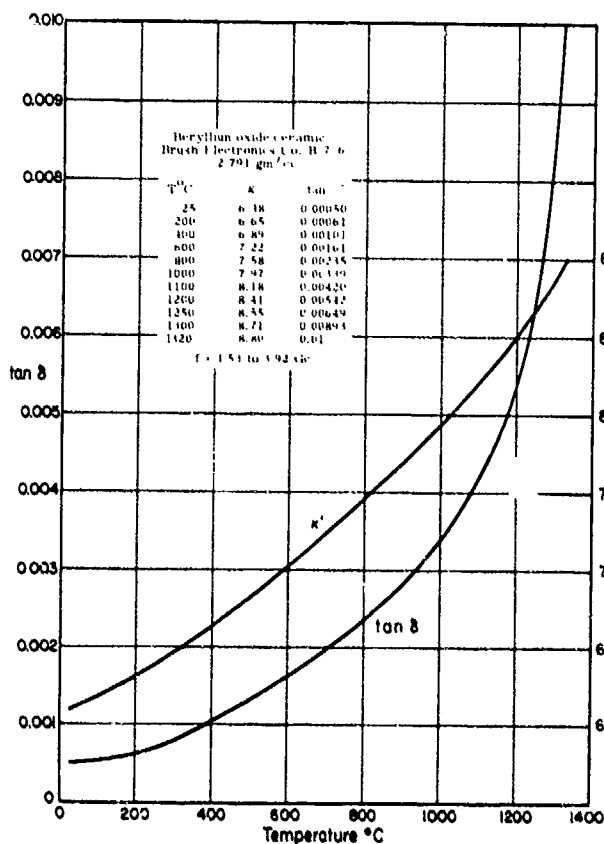
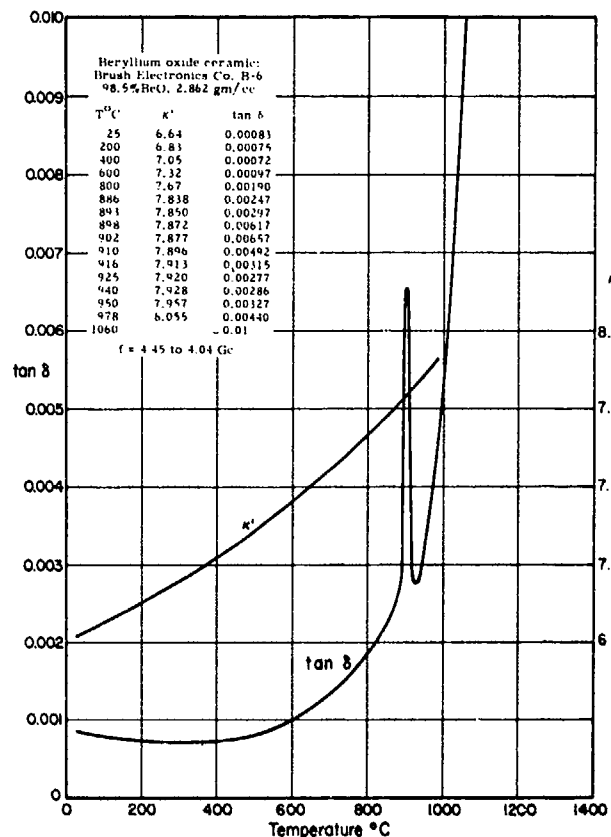
American Lava

AlSiMag 754 (99.5% BeO)

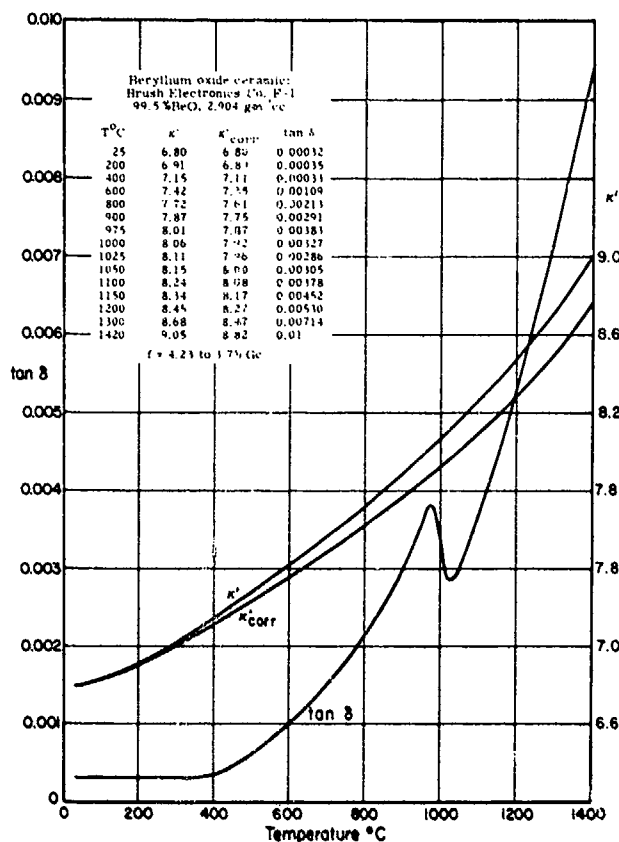
Density 2.851 g/cm<sup>3</sup>

8.52 GHz

T °C	$\kappa'$	$\tan \delta$
25	6.86	.00031
300	6.98	.00055
500	7.13	.00062



# Beryllium oxide (cont.)

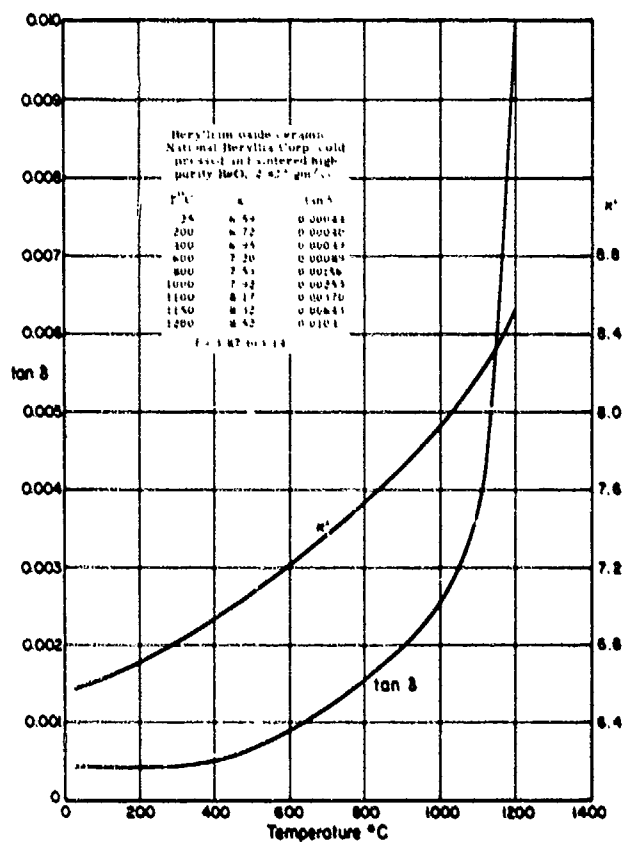


Coors Porcelain Co.

Beryllia BD98

8.52 GHz

T°C	$\kappa'$	$\tan \delta$
25	6.67	.00050
300	6.87	.00072
500	7.13	.00102



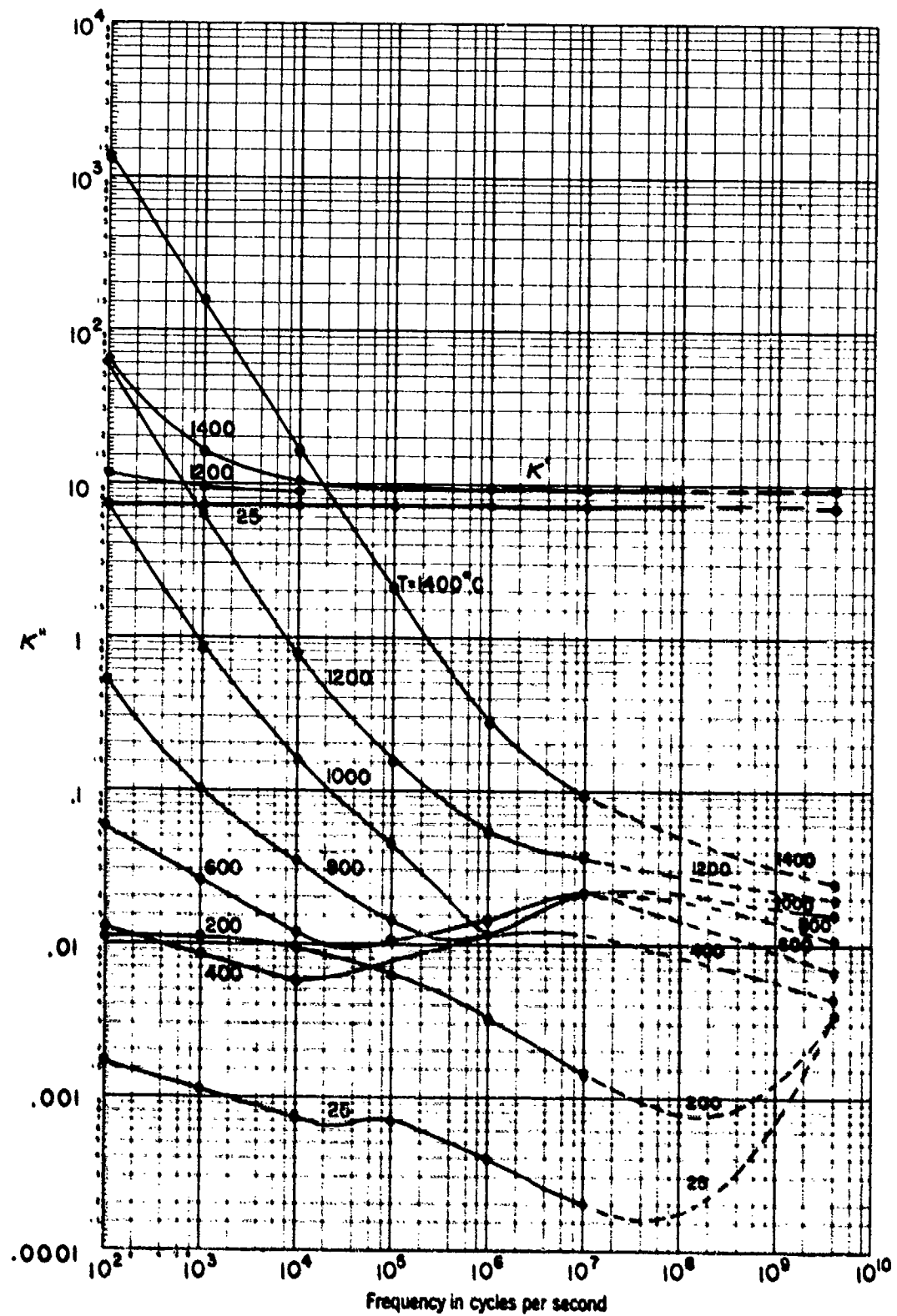
National Beryllia Corp.

Berlox

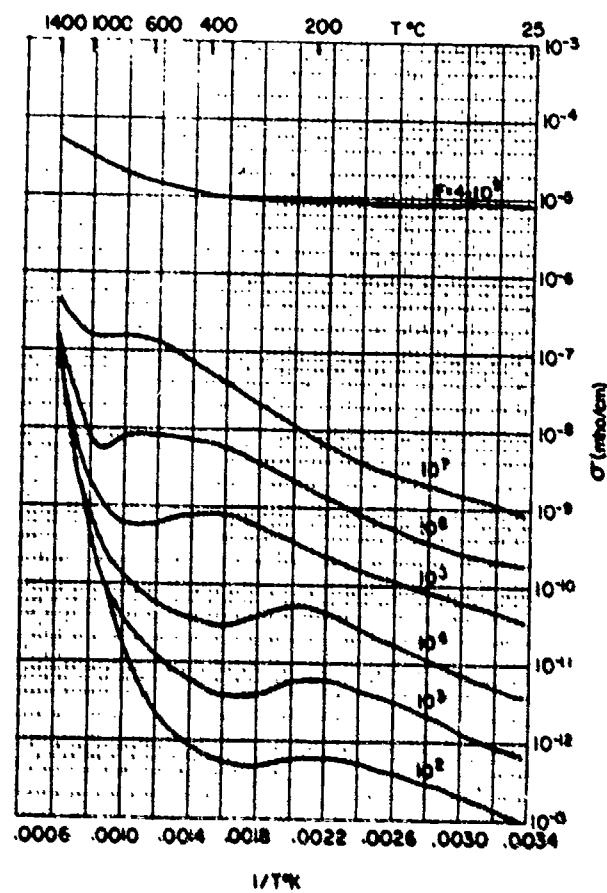
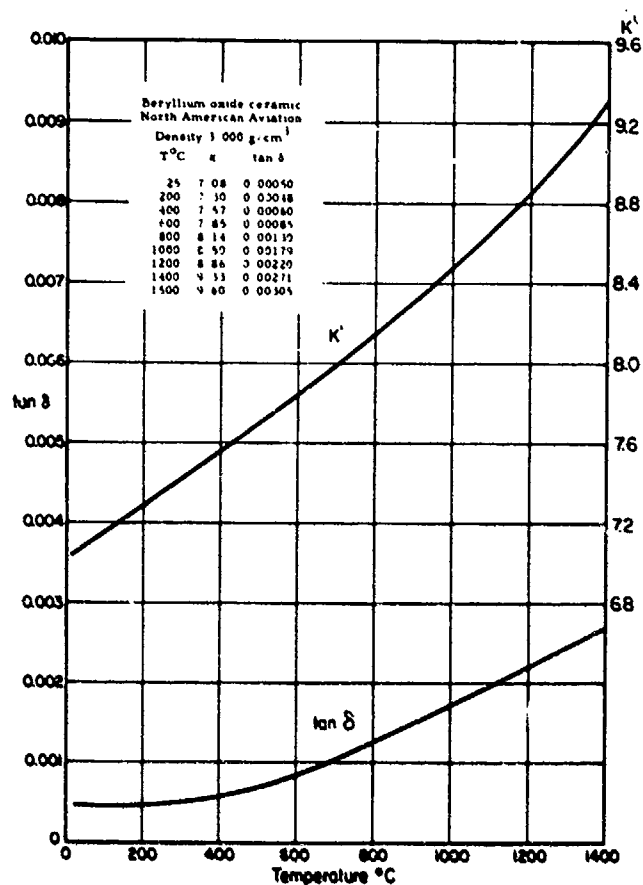
8.52 GHz

T°C	$\kappa'$	$\tan \delta$
25	6.64	.00043
300	6.77	.00068
500	6.98	.00093





# Beryllium oxide, multicrystal



Beryllium silicate crystal KSC 7013

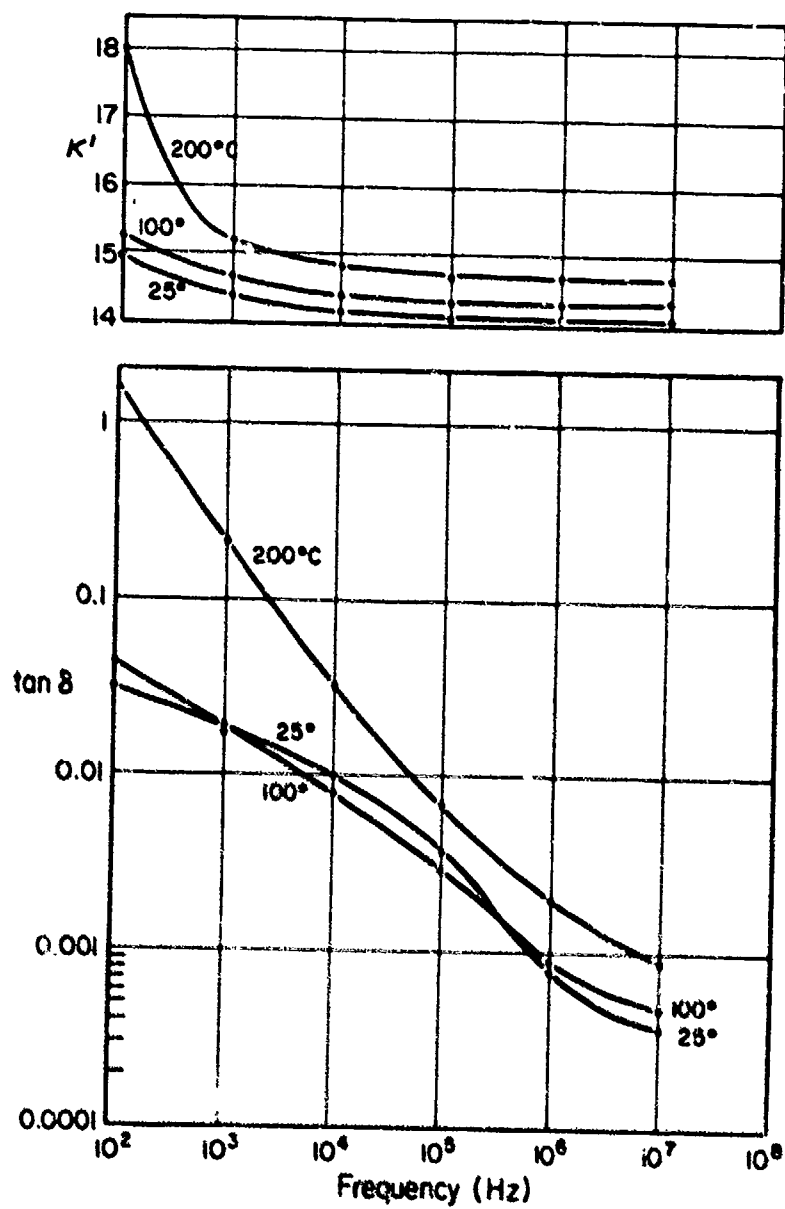
Electronic Space Products Inc.

E || optic axis

f (Hz)	$\kappa'$	$\tan \delta$
$10^2$	$5.1 \pm .5$	.0025
$10^5$	"	$.0003 \pm 2$

$\text{Bi}_4\text{Si}_3\text{O}_{12}$  ceramic

Laboratory for Insulation Research

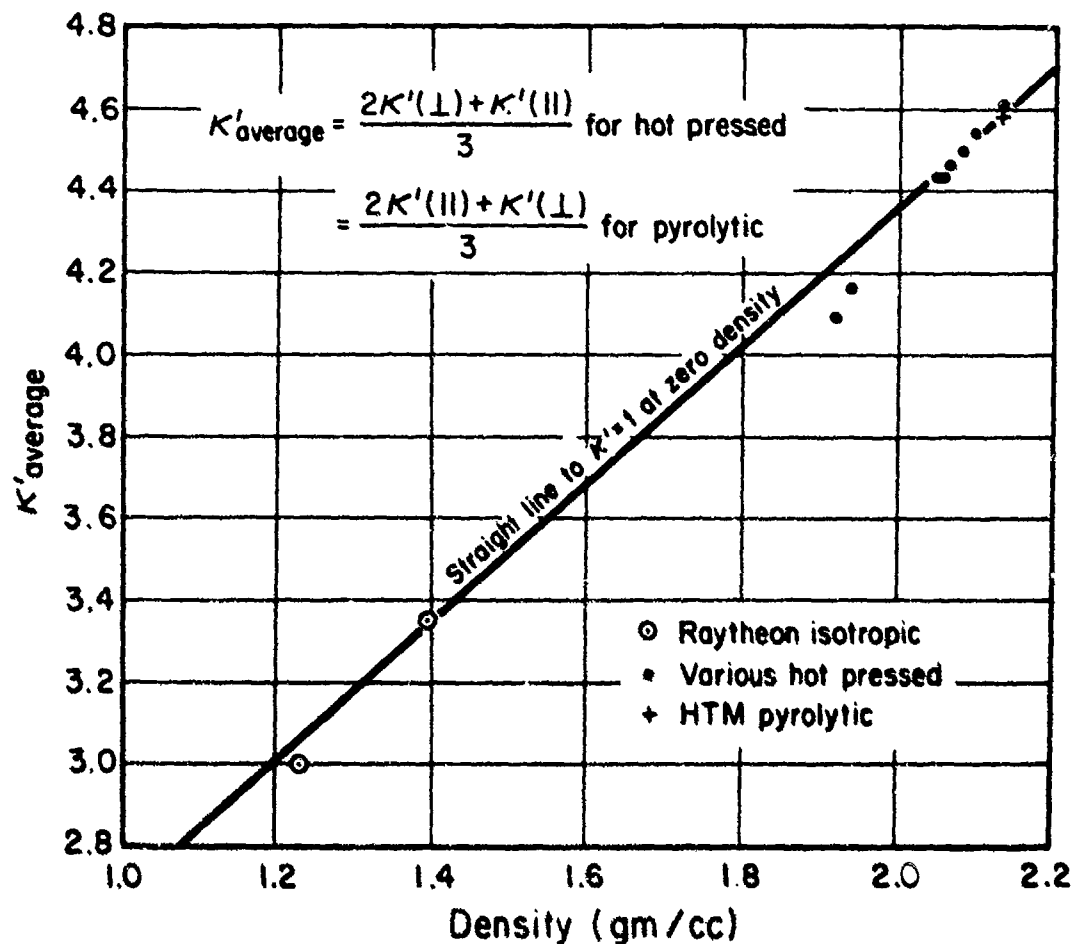


Boron nitride, hexagonal,

3000°C sublimes

Average dielectric constant versus density

X-ray density 2.25 g/cm<sup>3</sup>



Boron nitride

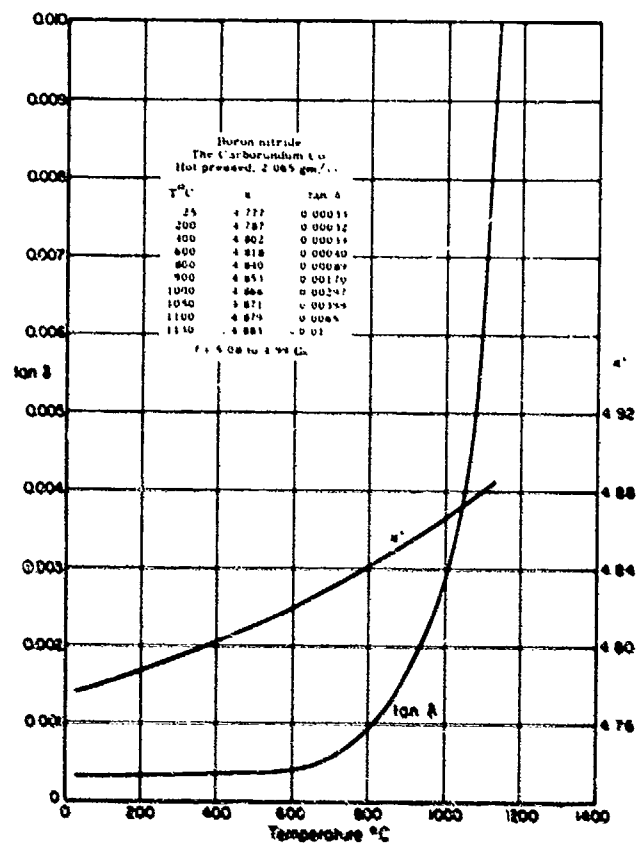
Battelle Memorial Institute

(hot-pressed, after vacuum treatment)

Density in g/cm<sup>3</sup>

8.52 GHz, 25°C

Sample	Density	$\kappa$	$\tan \delta$
115H7	—	4.37	.00030
118H7	2.132	4.87	.00025



Boron nitride, hot-pressed  
Grade A, 25°C

Carborundum

All tan  $\delta$  values are multiplied by  $10^4$

Sample No.	Density (g/cm <sup>3</sup> )	Field direct.	(Hz)	$10^2$	$10^3$	$10^4$	$10^5$	$10^6$	$10^7$	$10^8$
1	2.084	unknown	$\kappa$	4.13	4.12	4.090	4.087	4.086	4.080	4.08
			tan $\delta$	11.8	10.4	7.9	4.3	3.1	2.7	2.6
2	2.040	$\perp$	$\kappa$	4.40	4.40	4.39	4.39	4.39	4.38	
			tan $\delta$	8.7	6.3	6.0	3.1	1.8	1.0	
3	2.066	$\parallel$	$\kappa$	3.99	3.99	3.98	3.98	3.98	3.97	
			tan $\delta$	6.9	5.6	4.5	3.0	2.4	1.1	
				(Hz) $3 \times 10^8$	$10^9$	$3 \times 10^9$	$8.5 \times 10^9$	$1.4 \times 10^{10}$	$2.4 \times 10^{10}$	
4 (various not meas.)		unknown	$\kappa$	4.46	4.46	4.46		4.6	4.61	
			tan $\delta$	4.0	3.3	3.4		5.8	3.5	
5	2.099	unknown	$\kappa$				4.605			
			tan $\delta$				20			
6	2.091	$\perp$	$\kappa$	4.62	4.615	4.599				
			tan $\delta$	2.6	3.7	3.8				
7	2.097	mixed	$\kappa$	4.36	4.359	4.352				
			tan $\delta$	2.2	1.3	1.5				
8	2.069	$\perp$	$\kappa$				4.586			
			tan $\delta$				6.4			
9	2.077	$\perp$	$\kappa$				4.550			
			tan $\delta$				3.6			
9	"	$\parallel$	$\kappa$				4.268			
			tan $\delta$				4.5			
10		$\perp$	$\kappa$					4.268		
			tan $\delta$					4.5		
11	2.093	$\perp$	$\kappa$					4.53		
			tan $\delta$					4.5		
11	"	$\parallel$	$\kappa$					4.28		
			tan $\delta$					10.4		
12	2.090	$\perp$	$\kappa$						4.56	
			tan $\delta$						5.3	
13	2.095	$\perp$	$\kappa$						4.54	
			tan $\delta$						4.6	
13	"	$\parallel$	$\kappa$						4.24	
			tan $\delta$						3.2	

Boron nitride, hot-pressed  
Grade HP, 25°C

The Carborundum Company  
Refractories & Electronics Division  
Whirlpool Technical Center  
Niagara Falls, N.Y., 14302

All tan  $\delta$  values multiplied by  $10^4$

Sample No.	Density (g/cm <sup>3</sup> )	Field direct.	(Hz)	10 <sup>2</sup>	10 <sup>3</sup>	10 <sup>4</sup>	10 <sup>5</sup>	10 <sup>6</sup>	10 <sup>7</sup>	10 <sup>8</sup>
1	2.120	unknown	$\kappa$	4.59	4.56	4.54	4.54	4.54	4.54	4.54
			tan $\delta$	8.5	3.58	2.30	2.3	2.3	2.8	3.5
2	1.762	$\perp$	$\kappa$	4.14	4.02	3.97	3.96	3.96	3.96b	
			tan $\delta$	414	174	41.6	9.9	3.4	2.0	
3	2.131	$\parallel$	$\kappa$	4.71	4.64	4.54	4.46	4.40	4.32	
			tan $\delta$	100	110	120	125	141	123	
			(Hz)	$3 \times 10^8$	$10^9$	$3 \times 10^9$	$8.5 \times 10^9$	$1.4 \times 10^{10}$	$2.4 \times 10^{10}$	
4 (various not meas.)		unknown	$\kappa$	4.59	4.59	4.59	4.39	4.62	4.57	
			tan $\delta$	2.7	3.5	4.2	6.55	6.0	6.0	
5	1.999	unknown	$\kappa$							
			tan $\delta$							
6	2.033	$\perp$	$\kappa$	4.47	4.468	4.457				
			tan $\delta$	5.3	4.6	6.0				
7	1.748	mixed	$\kappa$	3.88	3.880	3.876				
			tan $\delta$	4.1	4.7	4.0				
8	2.111	$\perp$	$\kappa$				4.584			
			tan $\delta$				8.0			
9	2.061	$\perp$	$\kappa$				4.552			
			tan $\delta$				7.1			
9	"	$\parallel$	$\kappa$				4.507			
			tan $\delta$				7.7			
10	2.117	$\perp$	$\kappa$					4.75		
			tan $\delta$					8.0		
11	2.063	$\perp$	$\kappa$					4.55		
			tan $\delta$					8.7		
11	"	$\parallel$	$\kappa$					4.51		
			tan $\delta$					8.8		
12	2.118	$\perp$	$\kappa$							4.69
			tan $\delta$							8.5
13	2.066	$\perp$	$\kappa$							4.61
			tan $\delta$							7.7
13	"	$\parallel$	$\kappa$							4.48
			tan $\delta$							9.2

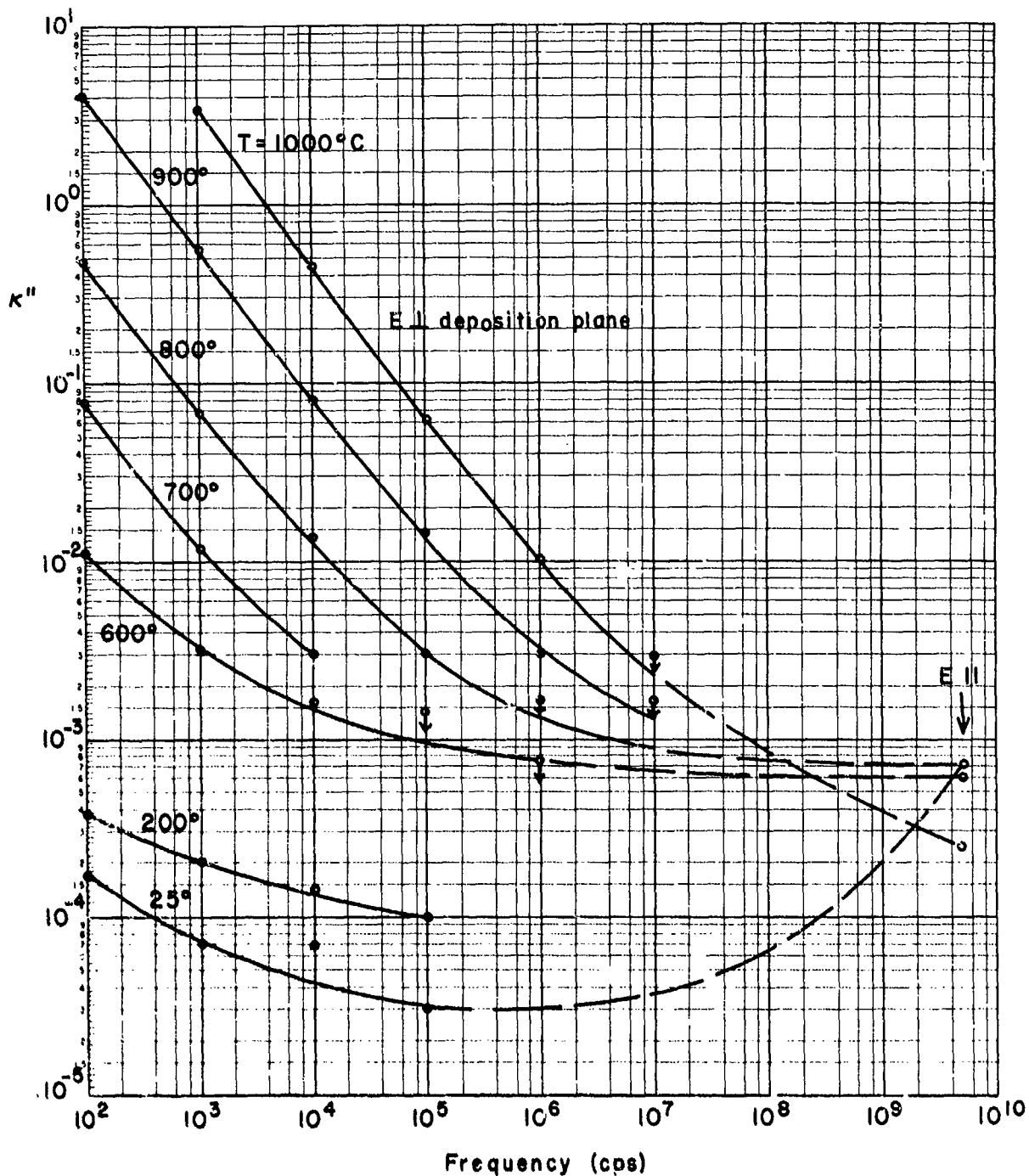
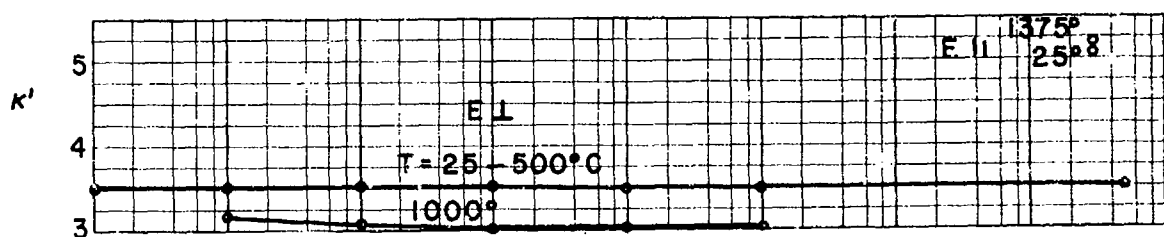
Boron nitride, hot-pressed, with silica  
Grade M, 25°C

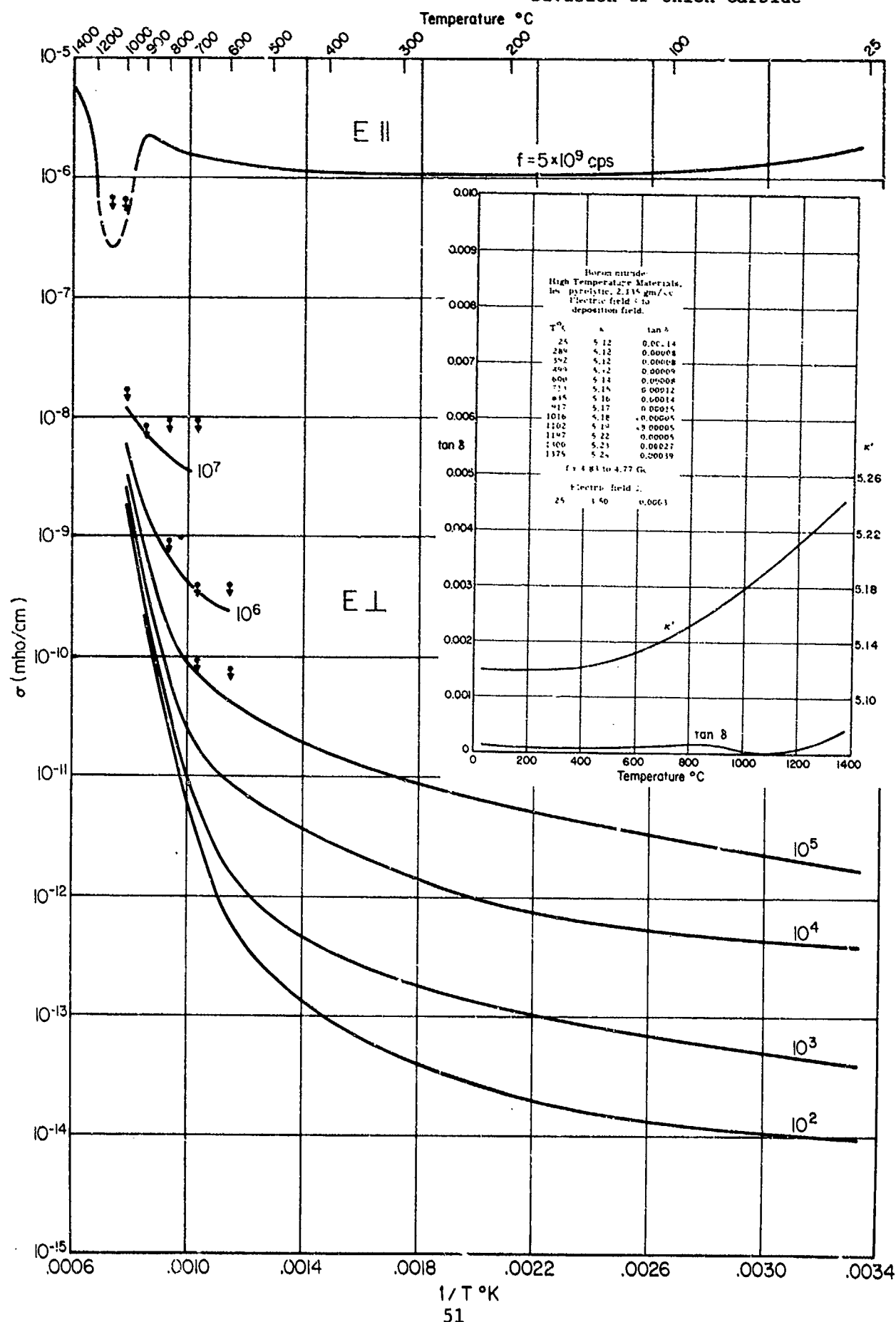
Carborundum

Sample No.	Density (g/cm <sup>3</sup> )	Field direct.	(Hz)	All tan $\delta$ values multiplied by 10 <sup>4</sup>						
				10 <sup>2</sup>	10 <sup>3</sup>	10 <sup>4</sup>	10 <sup>5</sup>	10 <sup>6</sup>	10 <sup>7</sup>	10 <sup>8</sup>
1	2.143	unknown	$\kappa$	3.71	3.70	3.69	3.69	3.69	3.68	3.68
			tan $\delta$	4.0	2.78	2.22	2.07	1.63	1.8	2.3
2	2.107	⊥	$\kappa$	4.34	4.33	4.32	4.30	4.30	4.30	
			tan $\delta$	16.9	14.3	10.5	6.6	3.7	1.9	
3	2.109		$\kappa$	3.76	3.76	3.76	3.75	3.75	3.75	
			tan $\delta$	7.4	7.0	6.7	4.6	3.4	3.6	
4	(various not meas.)		(Hz) $\kappa$	3x10 <sup>8</sup>	10 <sup>9</sup>	3x10 <sup>9</sup>	8.5x10 <sup>9</sup>	1.4x10 <sup>10</sup>	2.4x10 <sup>10</sup>	
			tan $\delta$	4.24	4.24	4.24		4.32		
5	2.145		$\kappa$	2.8	3.1	3.7		5.5		
			tan $\delta$				4.328			
6	2.137	⊥	$\kappa$				4.1			
			tan $\delta$	4.27	4.27	4.255				
7	2.118	mixed	$\kappa$	3.8	4.9	4.9				
			tan $\delta$	3.99	3.992	3.983				
8	2.095	⊥	$\kappa$	3.9	4.5	5.2				
			tan $\delta$				4.192			
9	2.120	⊥	$\kappa$				6.6			
			tan $\delta$				4.332			
9			$\kappa$				6.2			
			tan $\delta$				3.668			
10	2.125	⊥	$\kappa$				8.5			
			tan $\delta$					4.23		
11	2.123	⊥	$\kappa$					5.4		
			tan $\delta$					4.293		
11	"	I	$\kappa$					11.0		
			tan $\delta$					3.63		
12	2.066	⊥	$\kappa$					7.8		
			tan $\delta$						4.22	
13	2.121	⊥	$\kappa$						6.1	
			tan $\delta$						4.28	
"			$\kappa$						7.9	
			tan $\delta$						3.64	
									10.5	



BN, pyrolytically deposited, High-Temperature Materials, Inc., "Boralloy." The microwave data show a small peak possibly due to loss of impurities (perhaps OH ions) at about 800°C. Graphite electrodes and prepurified N<sub>2</sub> used in low-frequency measurements which showed variations among different samples.

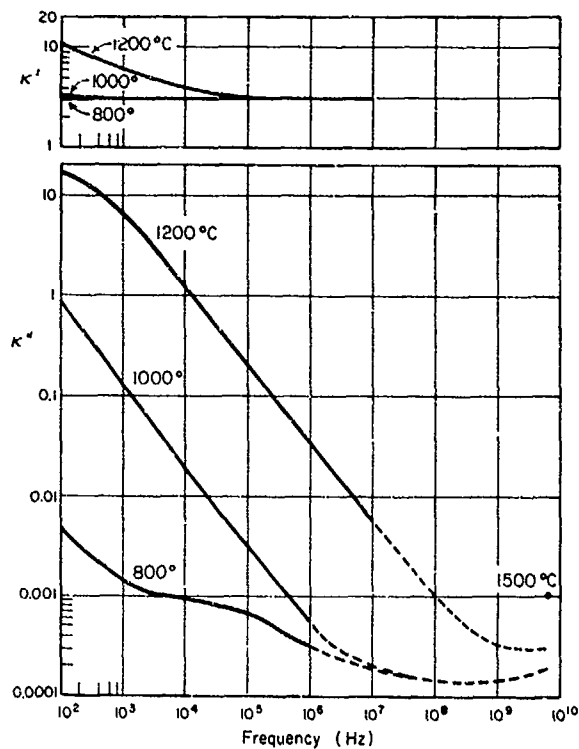




# Pyrolytic boron nitride

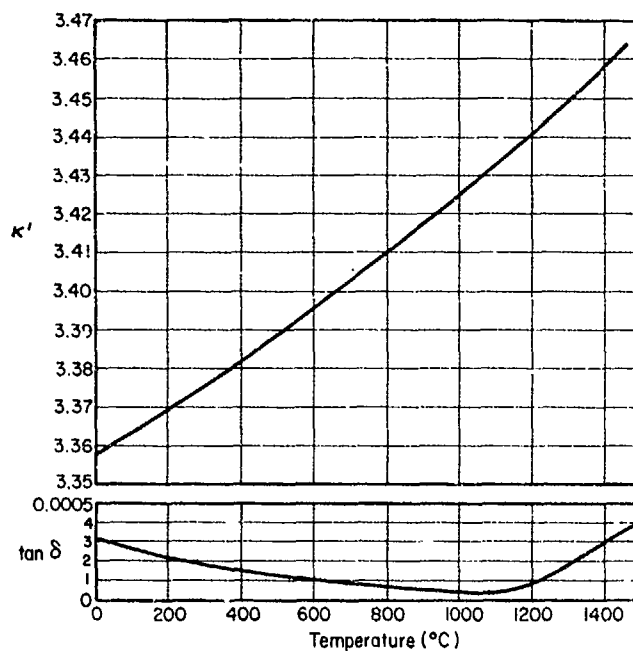
Raytheon

Density 1.23 g/cm<sup>3</sup>



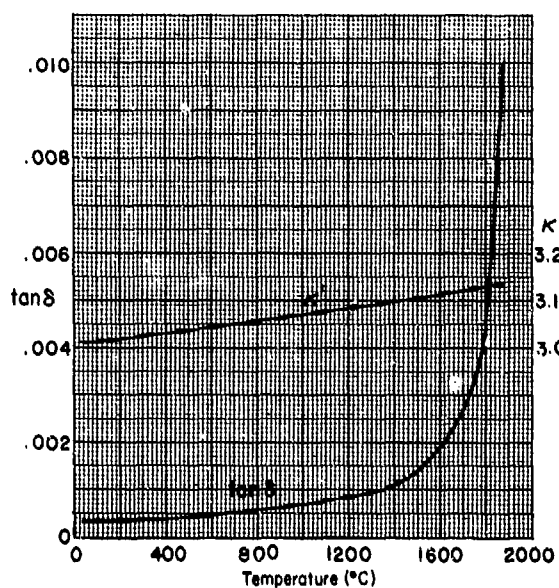
At 5.74 to 5.65 GHz

Density 1.398 g/cm<sup>3</sup>



Density 1.23 g/cm<sup>3</sup>

At 9.21 to 9.04 GHz



Boron nitride  
Pyrolytic

Raytheon Company

Post-treated samples, measured at 8.52 GHz, 25°C

Density (g/cm <sup>3</sup> )	$\kappa$	$\tan \delta$
1.233	2.994	.00008 $\pm$ .00002
1.237	3.013	.00005 $\pm$ .00003

Sample 2A + 2B, density at 25°C 1.381

T°C	5.07 to 5.00 GHz	
	$\kappa$	$\tan \delta$
25	3.199	<.0002
200	3.212	<.0002
400	3.226	<.0002
600	3.241	.0002 $\pm$ .0001
800	3.255	.0002 $\pm$ .0001
1000	3.272	.0002 $\pm$ .0001
1200	3.288	.0002 $\pm$ .0001
1300	3.297	.0003 $\pm$ .0002
1400	3.309	.0007 $\pm$ .0004

Test for anisotropic effects at 8.52 GHz, 25°C, by rotation and reversal of sample:

$$\kappa_{\max} = 3.0018$$

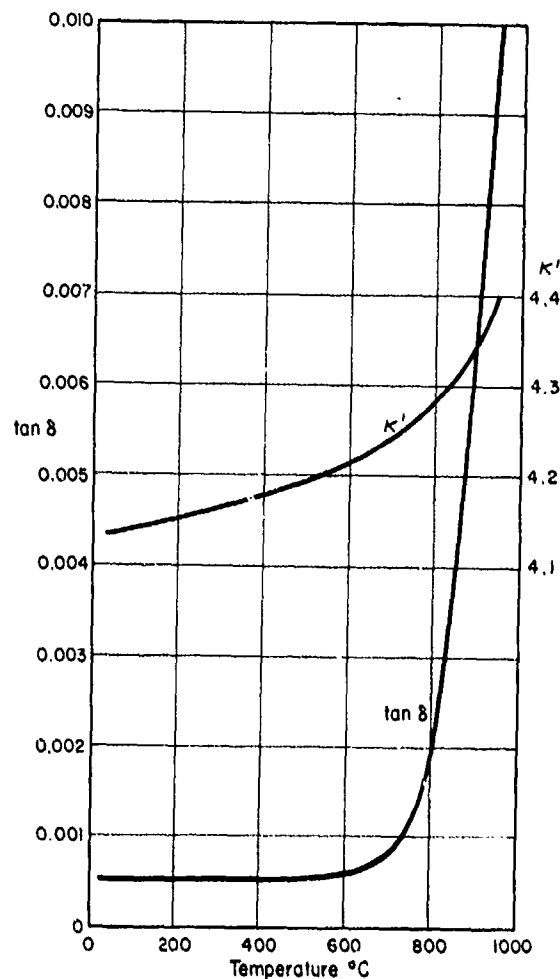
$$\kappa_{\min} = 2.9894$$

# Boron nitride

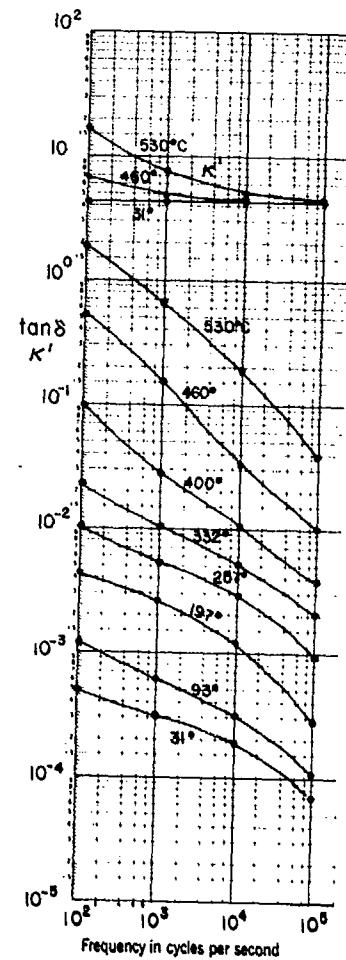
Pyrolytic laminate,  
Union Carbide

T °C		
25	5.15±.05	.00025±.00005
173		.00025±.0001
225		
341		
470		
610		
800		
978		.0003±.0001

Boron nitride,  
Grade HD0086, density 1.940 g/cm<sup>3</sup>,  
5.17 to 4.96 GHz



Boron nitride, hot-pressed  
Grade HD0056



Boron nitride, grade HD 0086

8.52 GHz

T °C	E	K'	tan delta
25		4.31	.00053
25	⊥	4.10	.00055
100	⊥	4.08	.00059
200	⊥	4.07	.00066
300	⊥	4.06	.00075
400	⊥	4.05	.00086
500	⊥	4.05	.00102

## Boron nitride, hot-pressed

Union Carbide

Grade HD 0092,

Density 1.9745 g/cm<sup>3</sup>

At 8.52 GHz

$\kappa_{\min} = 3.993 \quad \tan \delta = 0.00025$

$\kappa_{\max} = 4.091 \quad \tan \delta = 0.00026$

T°C	At 4.54 to 4.47 GHz	
	$\kappa$	$\tan \delta$
25	4.08	.00026
113	4.08	.0003
185	4.09	.0005
322	4.09	.00055
423	4.10	.00040
530	4.11	.00035
639	4.12	.00040
752	4.13	.00045
863	4.13	.00050
943	4.14	.00050
1021	4.15	.00055
1096	4.16	.00080
1170	4.16	.0013
1219	4.17	.0019
1287	4.18	.0034
1373	4.19	.0040
1427	4.20	.0028
1446	4.22	.0023
1460	4.24	.0044
1470	4.24	.0046

Grade HD 0093

Density 1.9165 g/cm<sup>3</sup>

At 8.52 GHz

$\kappa' = 3.998 \pm 0.002$

$\tan \delta = 0.00052$

T°C	At 4.53 to 4.44 GHz	
	$\kappa$	$\tan \delta$
25	4.003	.0005
207	4.048	.0004
393	4.072	.00045
513	4.088	.0004
593	4.101	.0007
798	4.146	.0030
852	4.166	.0052
891	4.204	.0040
1018	4.320	.0028
1077	4.479	.0057
1094	4.485	.0071
1110	4.54	.01
943	4.25	.0026
860	4.19	
25	4.01	

Density check after run 1.916

Grade HD 0094, at 8.52 GHz

Sample 2: density 1.303 g/cm<sup>3</sup>

T°C	$\kappa$	$\tan \delta$
25	3.004	.00033

Sample 1: density 1.307 g/cm<sup>3</sup>

T°C	$\kappa$	$\tan \delta$
25	3.016	.00033
93	3.02 $\pm$ .03	.00030
192		.00035
339		.00037
471		.00040
602	3.04 $\pm$ .03	.00040
705		.00047
754		.00060
793		.00095
843		.0020
954		.0085
999		.0135

At 5.30 to 5.26 GHz

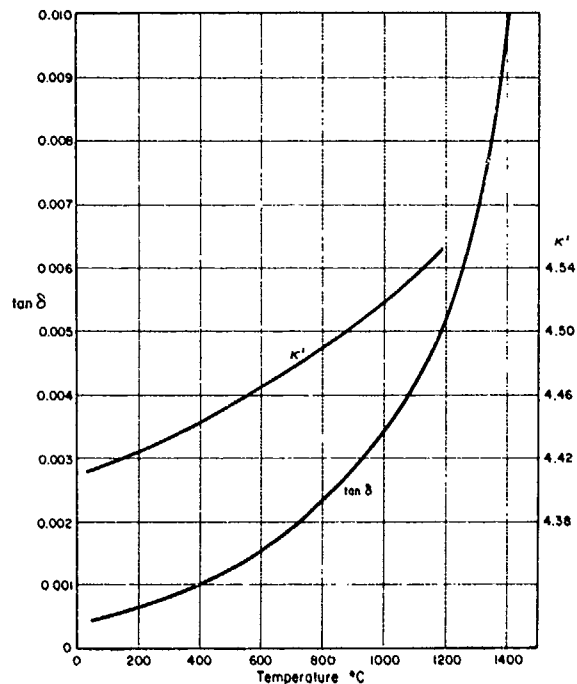
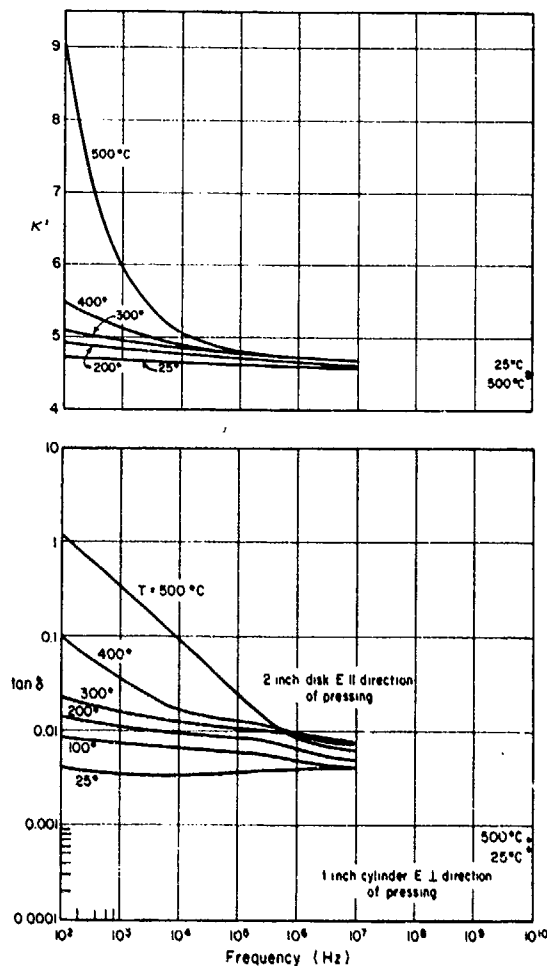
Density: 1.303 g/cm<sup>3</sup>

T°C	$\kappa$	$\tan \delta$
25	3.004	.00033
120	3.008	.00037
203	3.012	.00039
325	3.018	.00044
404	3.021	.00043
498	3.026	.00046
601	3.032	.00046
721	3.039	.00065
812	3.047	.00186
884	3.053	.00447
908		>.01

Hot-pressed boron nitride, grade HBN

Carbon Products Division  
Union Carbide Corp.  
(Formerly National Carbon Co.)

4.95 to 4.88 GHz



Density 2.054 g/cm<sup>3</sup>

1" cylinder, 8.52 GHz

T °C	E	$K'$	$\tan \delta$
25	⊥	4.38	.00050
25		4.52	.00056
100		4.52	.00056
200		4.51	.00061
300		4.50	.00064
400		4.49	.00066
500		4.48	.00073

Boron nitride, hot-pressed  
Grade HBR

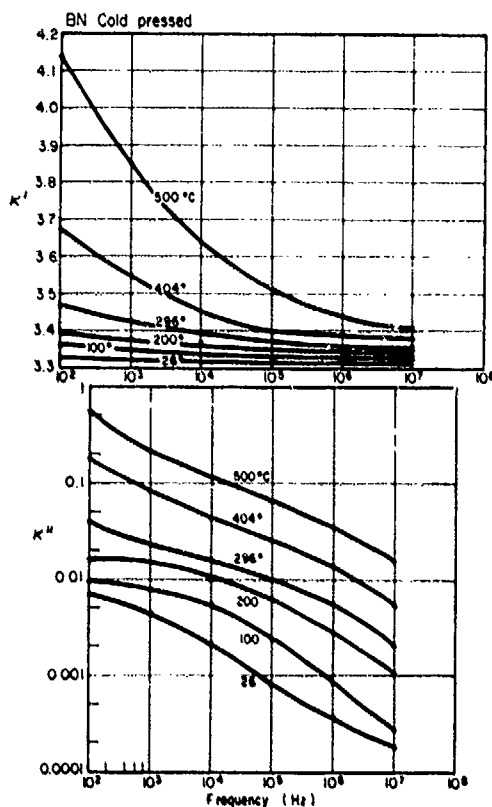
Union Carbide Corporation  
Carbon Products Division

E  $\perp$  direction of pressing

T°C		10 <sup>2</sup>	10 <sup>3</sup>	10 <sup>4</sup>	10 <sup>5</sup>	10 <sup>6</sup>	10 <sup>7</sup>
25	$\kappa$	4.77	4.77	4.76	4.76	4.76	4.76
	10 <sup>4</sup> tan $\delta$	18.2	7.1	4.9	1.5	1.4	0.9
100	$\kappa$	4.85	4.80	4.78	4.78	4.78	4.78
	10 <sup>4</sup> tan $\delta$	165	45.4	9.4	4.1	2.1	0.6
200	$\kappa$	5.26	4.96	4.85	4.82	4.81	4.81
	10 <sup>4</sup> tan $\delta$	596	277	101	39	5.4	23
300	$\kappa$	5.75	5.25	5.00	4.89	4.85	4.85
	10 <sup>4</sup> tan $\delta$	855	526	231	109	33.8	12.5
400	$\kappa$	6.75	5.70	5.21	5.00	4.88	4.87
	10 <sup>4</sup> tan $\delta$	28.0	11.57	4.95	2.3	1.2	.37
500	$\kappa$	8.07	6.46	5.62	5.31	5.08	4.93
	tan $\delta$	1.994	.389	.109	.0419	.024	.014

Boron nitride, Cold-pressed

Union Carbide Corporation



Rod sample, at 8.52 GHz

Density: 1.474 g/cm<sup>3</sup>

At 25°C:

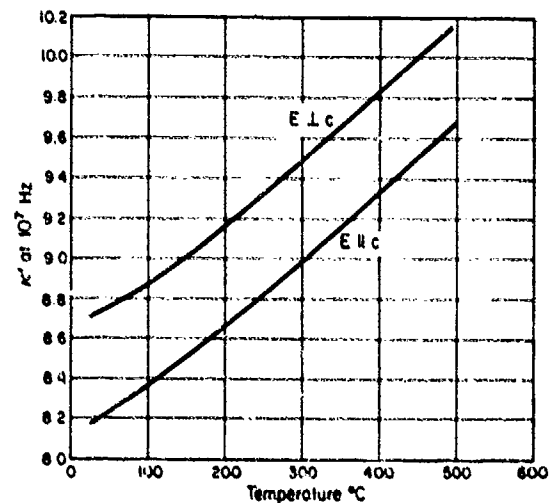
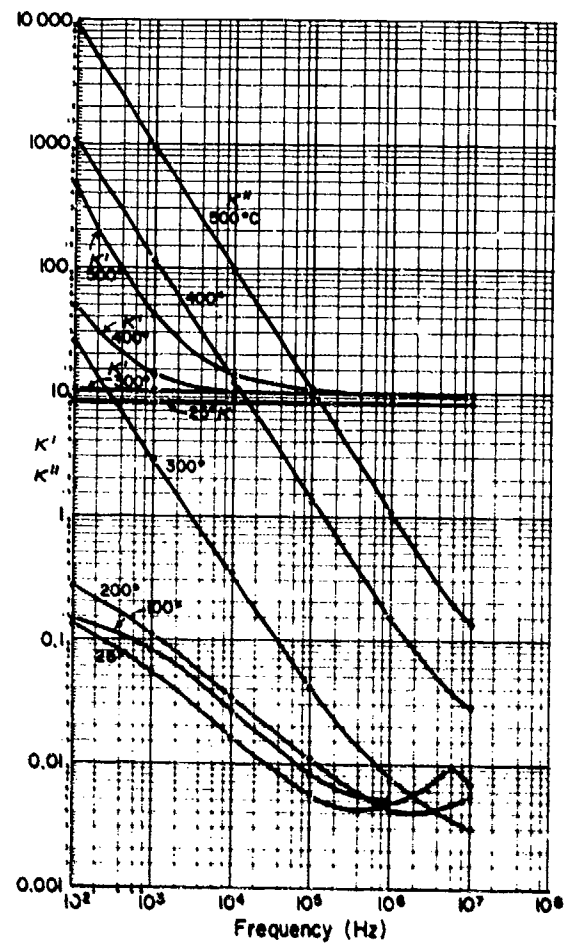
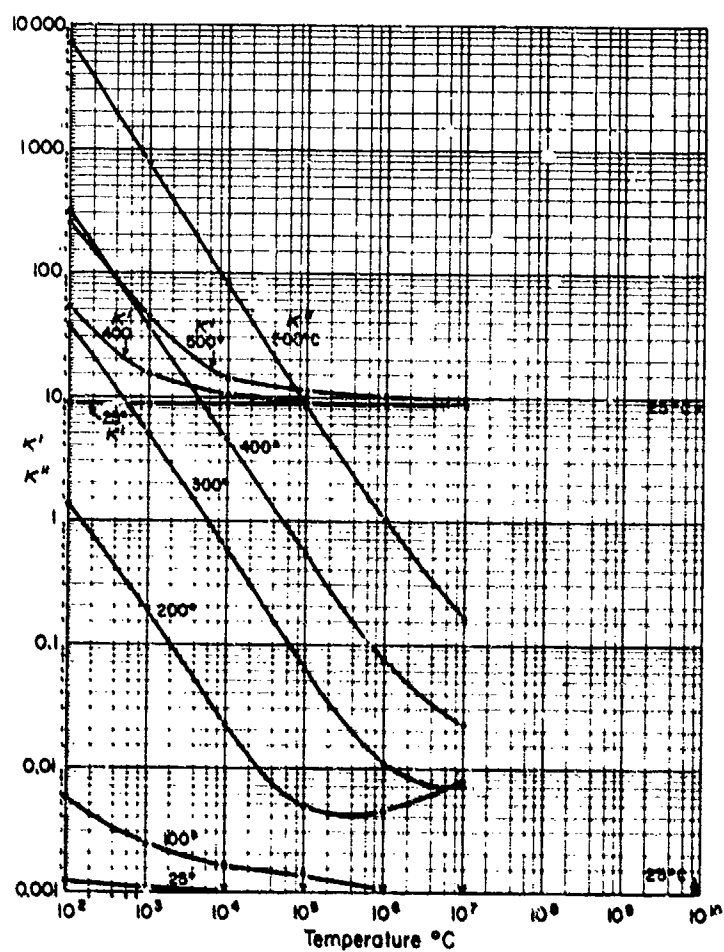
$$\kappa' = 3.412; \tan \delta = .00046$$



Calcium carbonate (calcite)  
Single crystal mineral,  
hexagonal, decomposes at 894°C

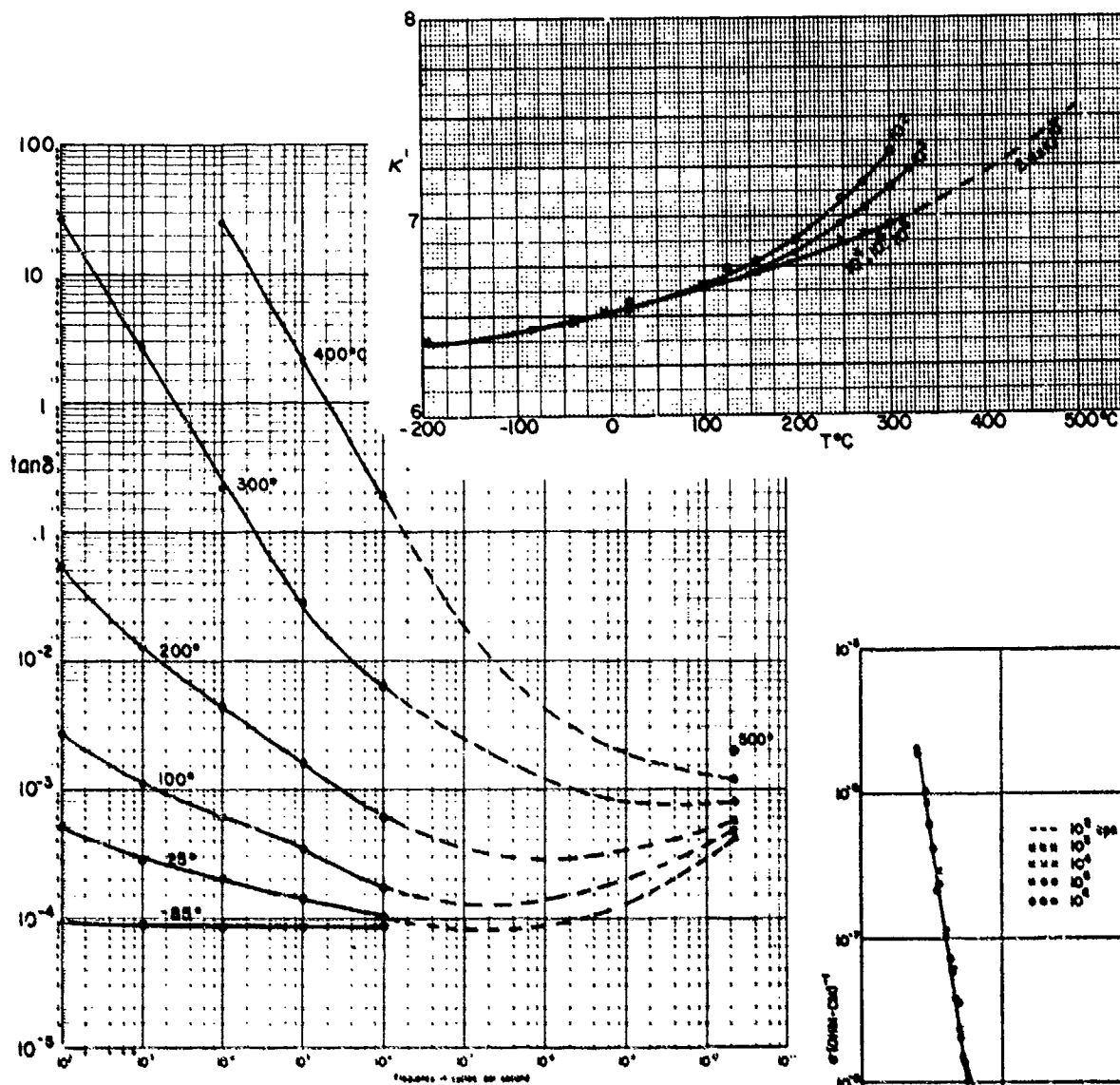
E || c, crystal No. 1

E ⊥ c, crystal No. 2

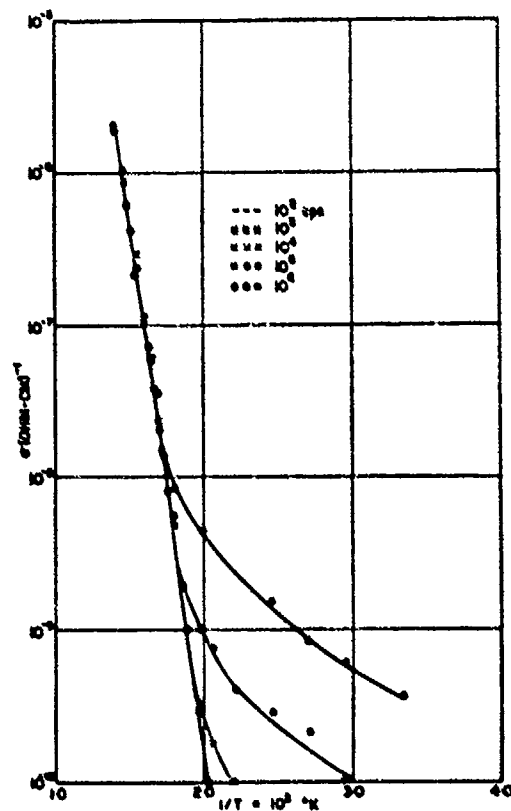


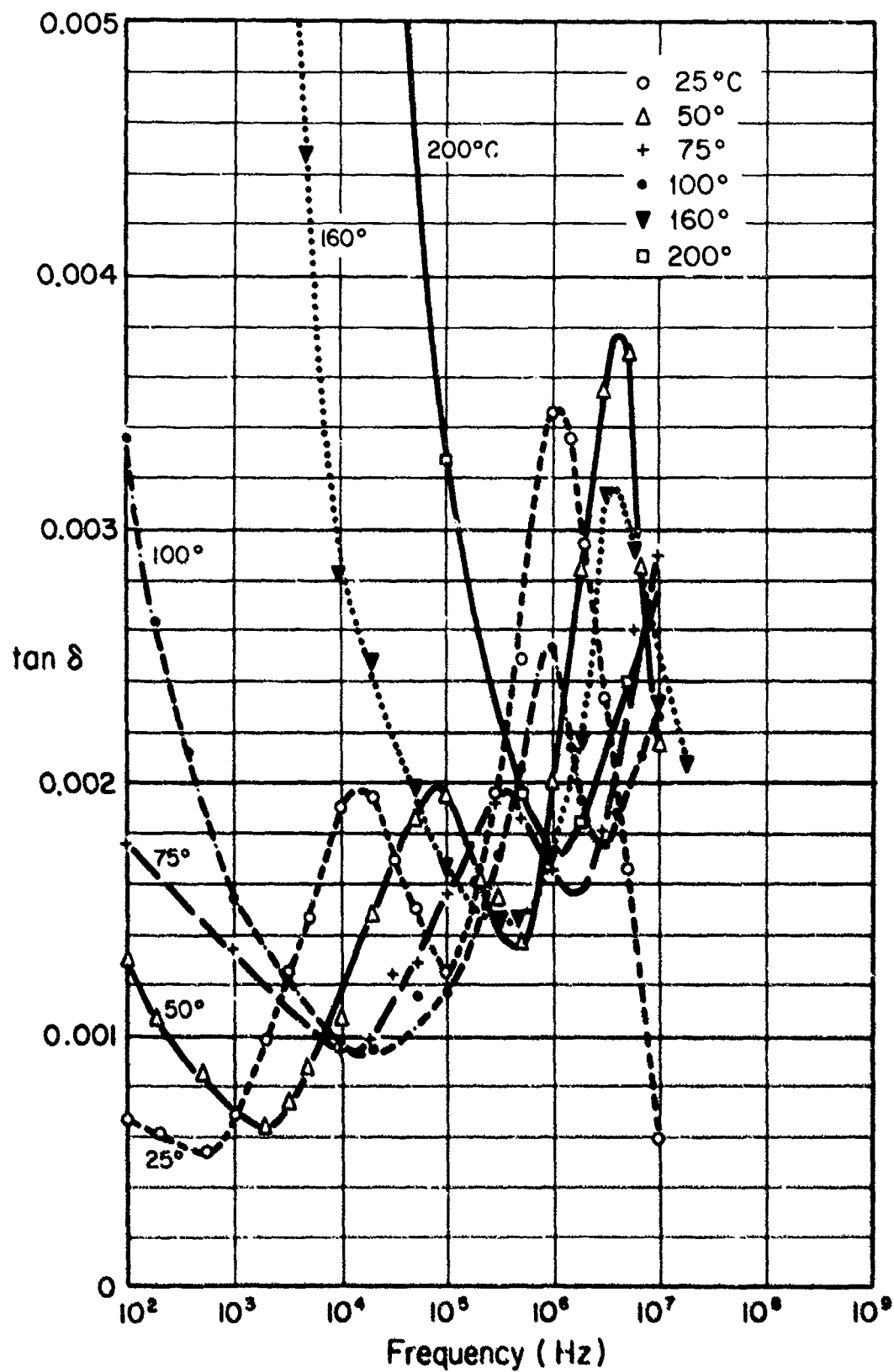
Calcium fluoride crystal  
Single crystal, cubic, m.p. 1360°C

M.I.T., Crystal Physics  
Laboratory



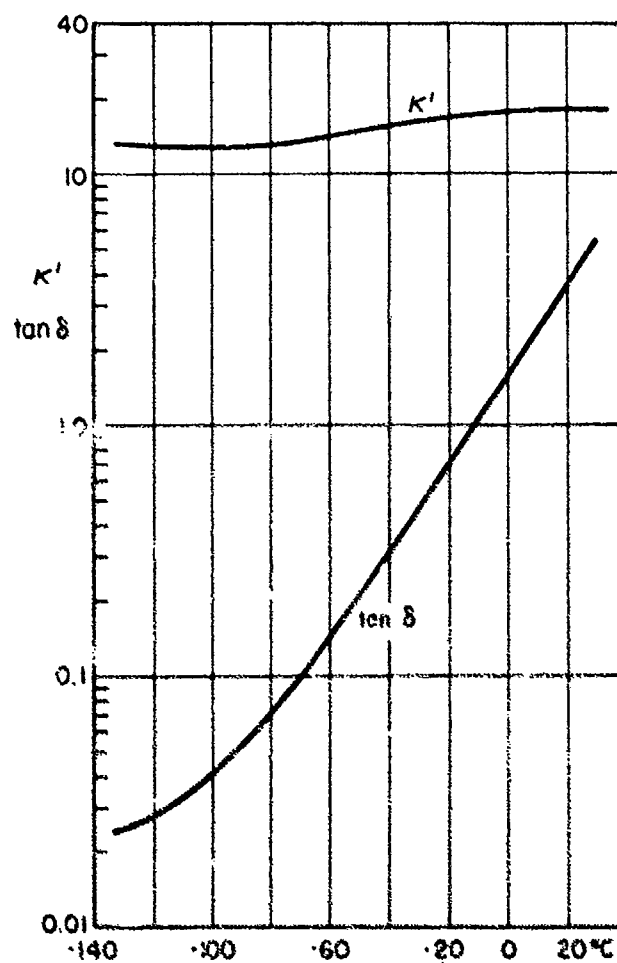
For more complete data see K. V. Rao  
and A. Smakula, J. Appl. Phys. 37,  
319 (1966).





Cerium fluoride, multicrystal,  
at 1 MHz

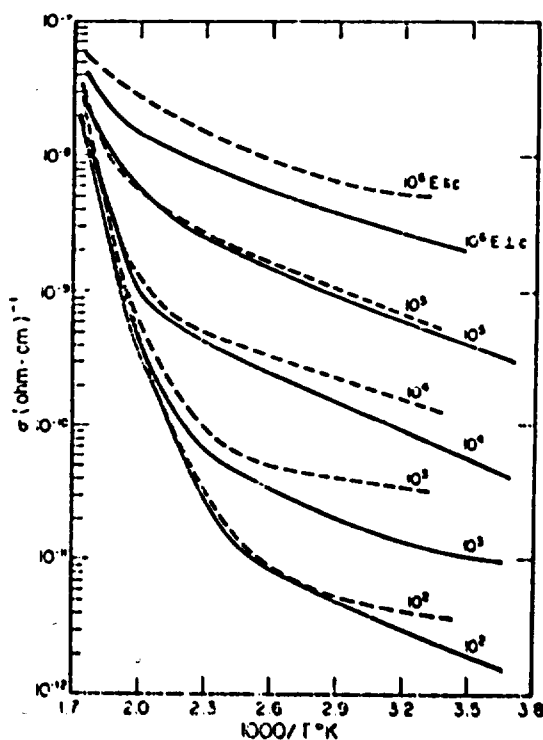
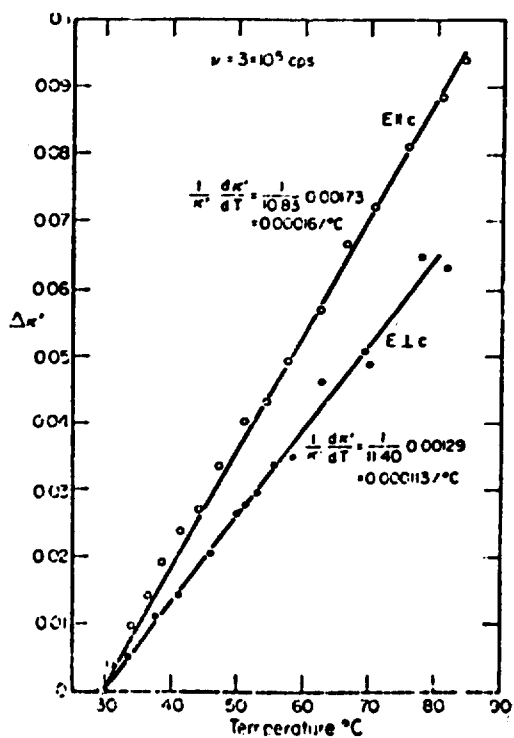
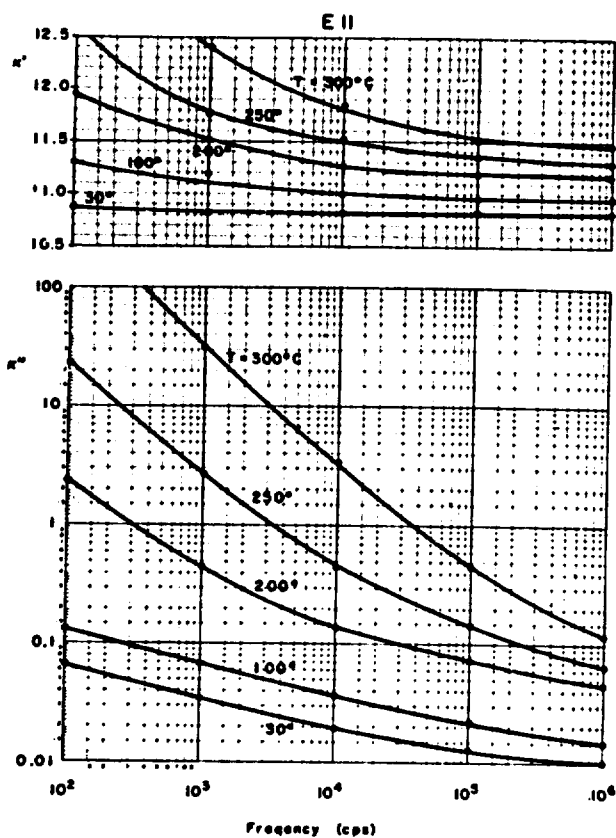
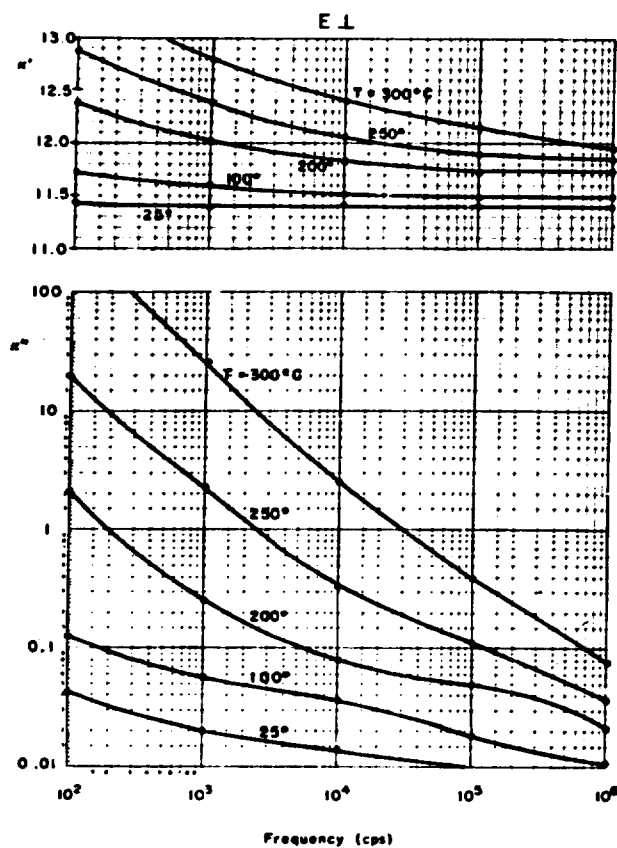
M.I.T., Laboratory for Insulation  
Research



	At 25°C	
Freq.	$10^5$	$6 \times 10^7$
$\kappa$	2.66	15.8
$\tan \delta$	3.86	0.253

$\text{Cr}_2\text{O}_3$  single crystal

The Linde Air Products Company



Cobalt oxide

Massachusetts Institute of Technology  
Crystal Physics Laboratory

Cobalt oxide-nickel oxide

At 25°C, 1 MHz

	$\kappa$	$\tan \delta$
CoO	12.9	.0005
CoO-NiO	40	.39

50/50 mole percent

For complete data see: K. V. Rao and A. Smakula, J. Appl. Phys.  
36, 2031 (1965).

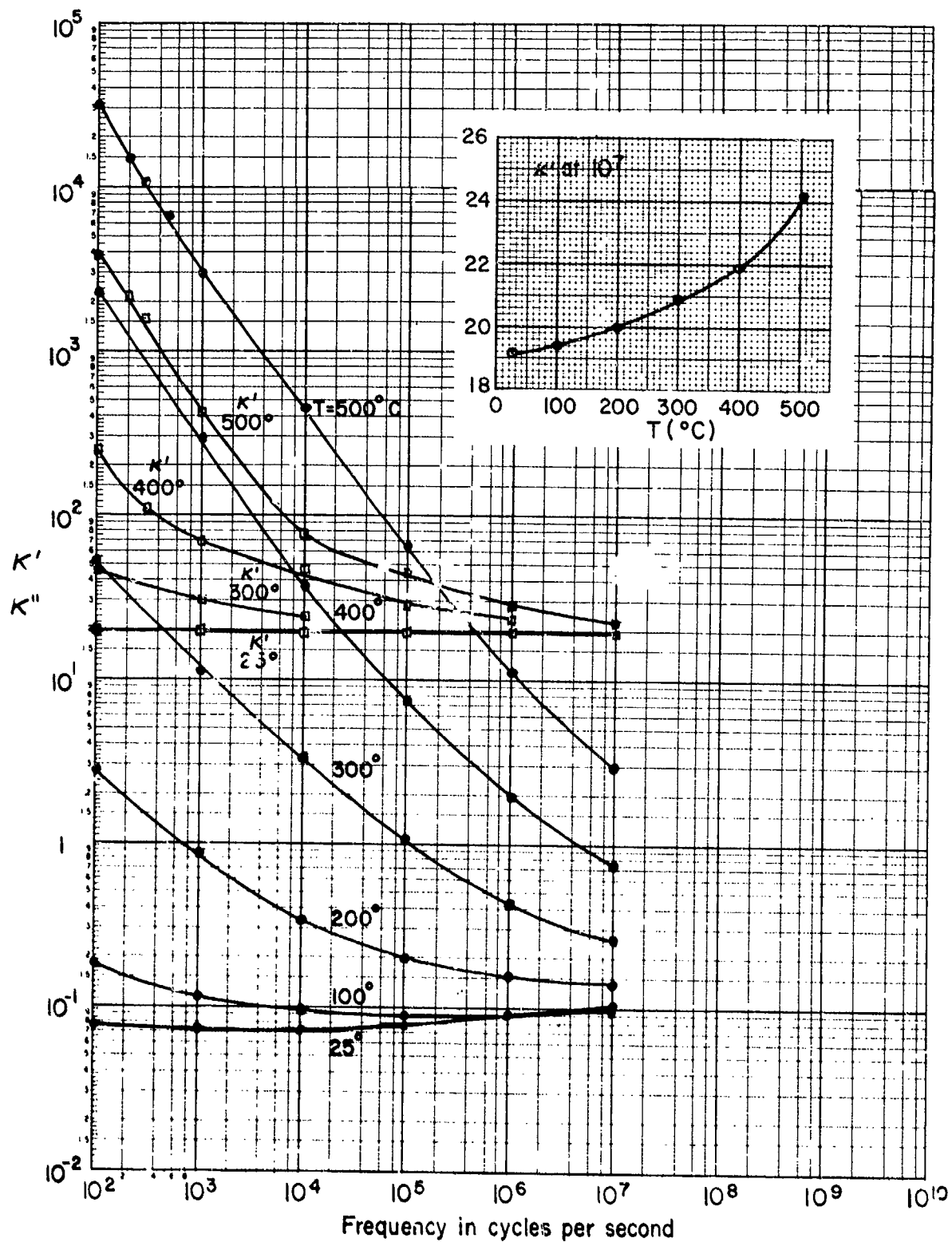
Copper halide pressed powders Massachusetts Institute of Technology  
Laboratory for Insulation Research

Measured values at 14 GHz

Sample density/X-ray density

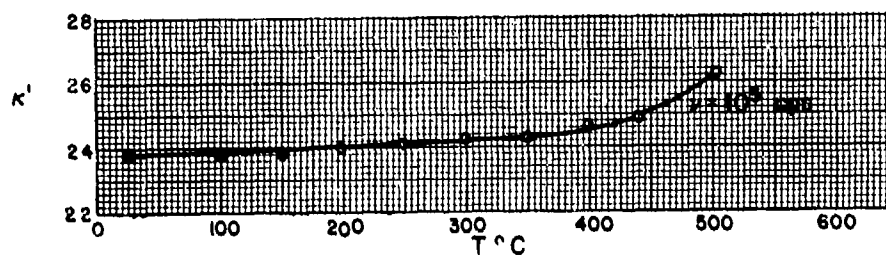
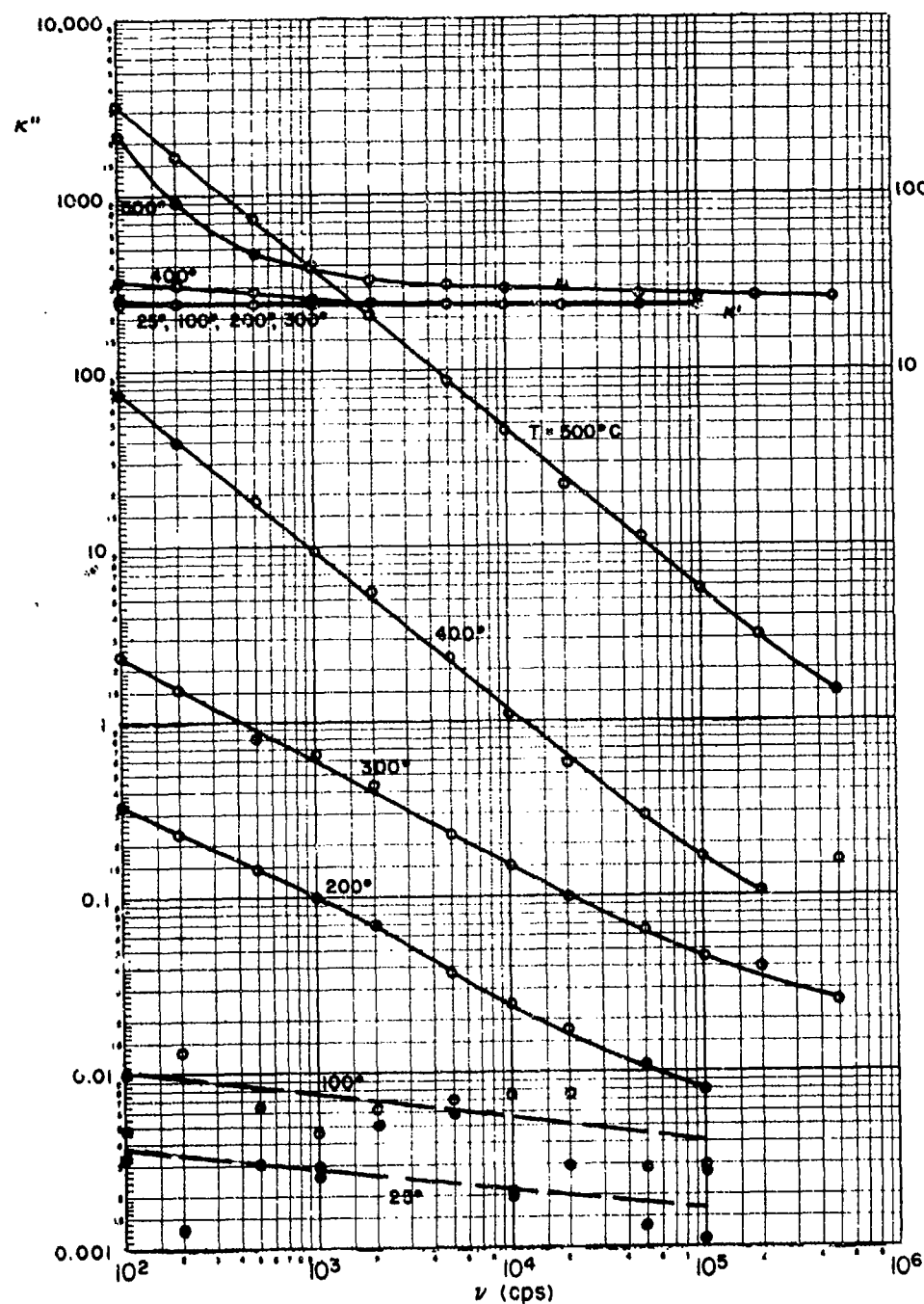
	$\kappa'$	$\tan \delta$
CuBr	4.85/5.17	$6.33 \times .001$
CuCl	3.68/4.10	$6.52 \times .001$
CuI		$27.8 \times .112$

Hafnium oxide (multicrystal) stabilized with  
 $\text{Y}_2\text{O}_3$ , nuclear grade Zircoa Y-790, density  
 $7.445 \text{ g/cm}^3$  (m.p.  $2810^\circ\text{C}$ ), see also p. 118



Lanthanum aluminate ( $\text{LaAlO}_3$ ),  
single crystal (m.p.  $1612^\circ\text{C}$ )  
Elec. field in  $[111]$  direction

National Lead





## Lead halides

## M. I. T. Crystal Physics Laboratory

	Electric field dir.		At 1 MHz, 25°C		Activation energy for "intrinsic" conduction
	parallel to		$\kappa'$	$\tan \delta$	
PbBr <sub>2</sub>	a	4.72	52.7	.0052	-
	b	8.06	56.3	.0033	-
	c	9.55	25.3	.0033	-
PbCl <sub>2</sub>	a	4.53	47.4	.11	.30 eV
	b	7.62	51.3	.065	.28 eV
	c	9.05	24.8	.051	.42 eV
PbCl <sub>2</sub> -PbBr <sub>2</sub> c 85/15 mol %			28.5	.016	1.1 eV

For additional data on these materials see: A. Smakula, Tech. Rep. No. 6,  
(Final Report under Contract Nonr 1841(88)), M. I. T., Crystal Phys. Lab.,  
March 11, 1965.

Magnesium aluminate (spinel) MgOAl<sub>2</sub>O<sub>3</sub>

Single crystal

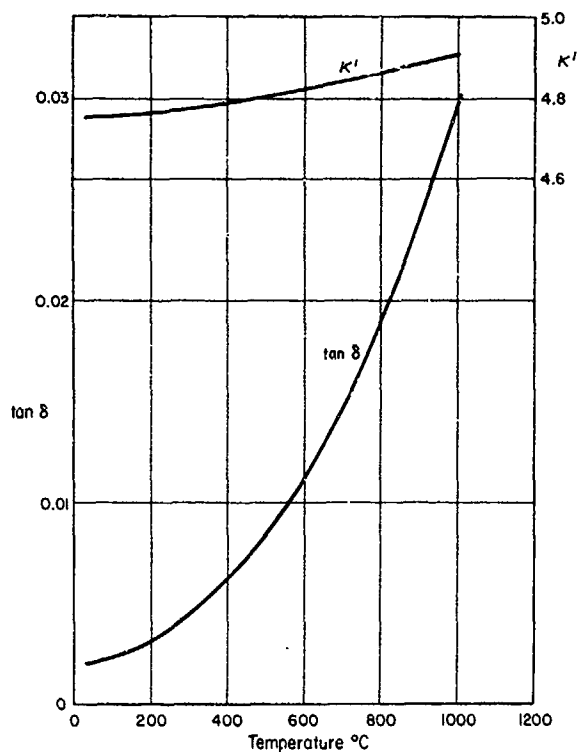
Union Carbide

Density at 25.0°, 3.57389 g/cm<sup>3</sup>At 8.52, 25°C:  $\kappa' = 8.26 \pm .04$  $\tan \delta = .00009 \pm .00002$ 

Freq. 4.23 - 4.07 GHz

T°C	$\kappa \pm 02$	$\tan \delta$
25	8.28	.0001
150	8.42	.0002
231	8.54	.0002
297	8.64	.0003
421	8.85	.0010
455	8.91	.0025

Magnesium aluminum silicate  
 Cordierite ceramic, at 8.52 GHz  
 Density 2.44 g/cm<sup>3</sup>  
 Raytheon Company



Magnesium carbonate, hard-packed  
 fine powder, reagent grade,  
 at 8.52 GHz, 25°C:

$K'$	$\tan \delta$
1.282	.0109

Density .189 g/cm<sup>3</sup>

Transparent MgO ceramic  
 IRTRAN-5  
 Density = 3.57 g/cm<sup>3</sup>, 25°C

Kodak

f (Hz)	$K'$	$\tan \delta$
10 <sup>2</sup>	9.82	.0014
8.5 × 10 <sup>9</sup>	9.72	.00045

Magnesium oxide, single crystal

Norton

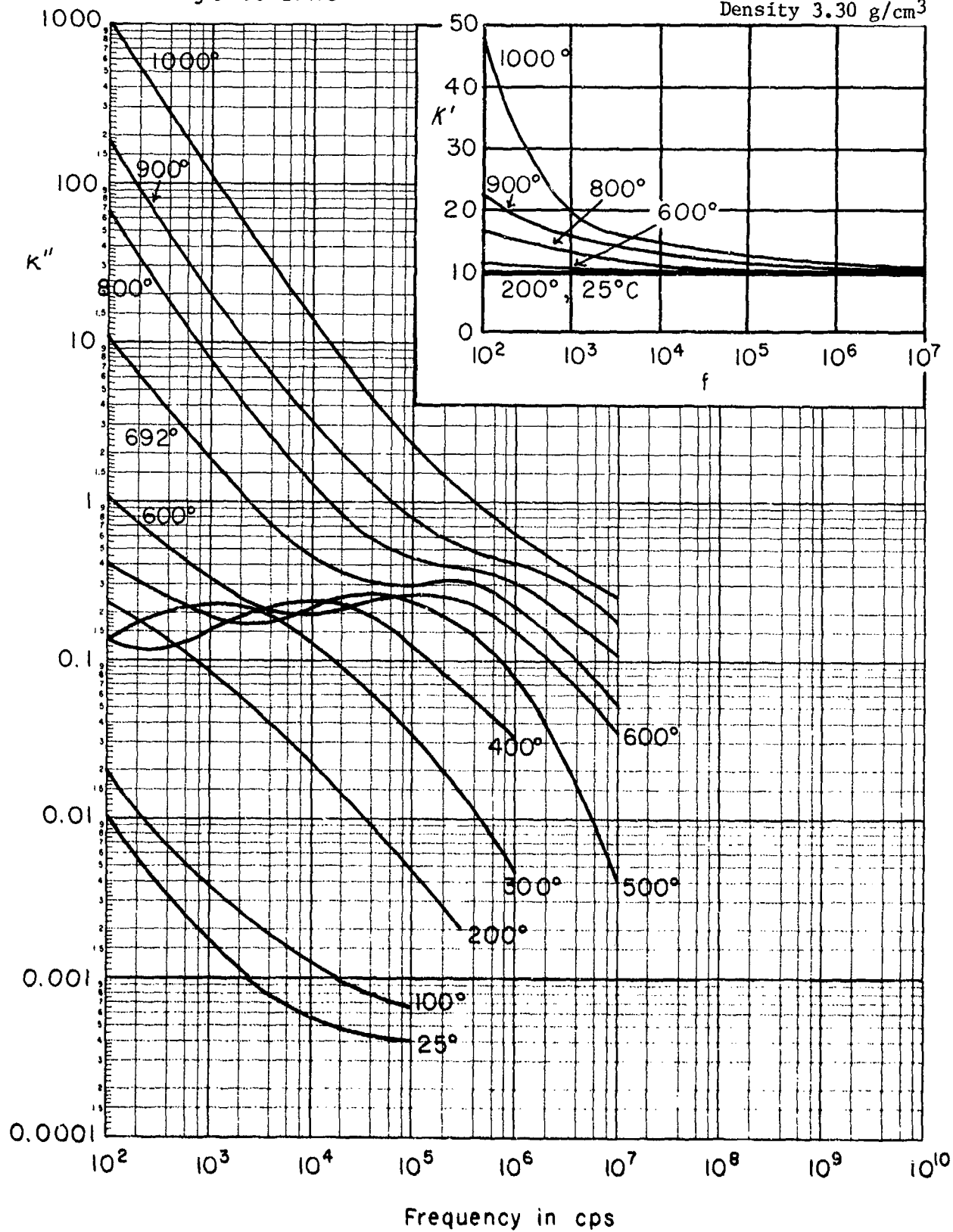
50 GHz

$\kappa'$   
9.72

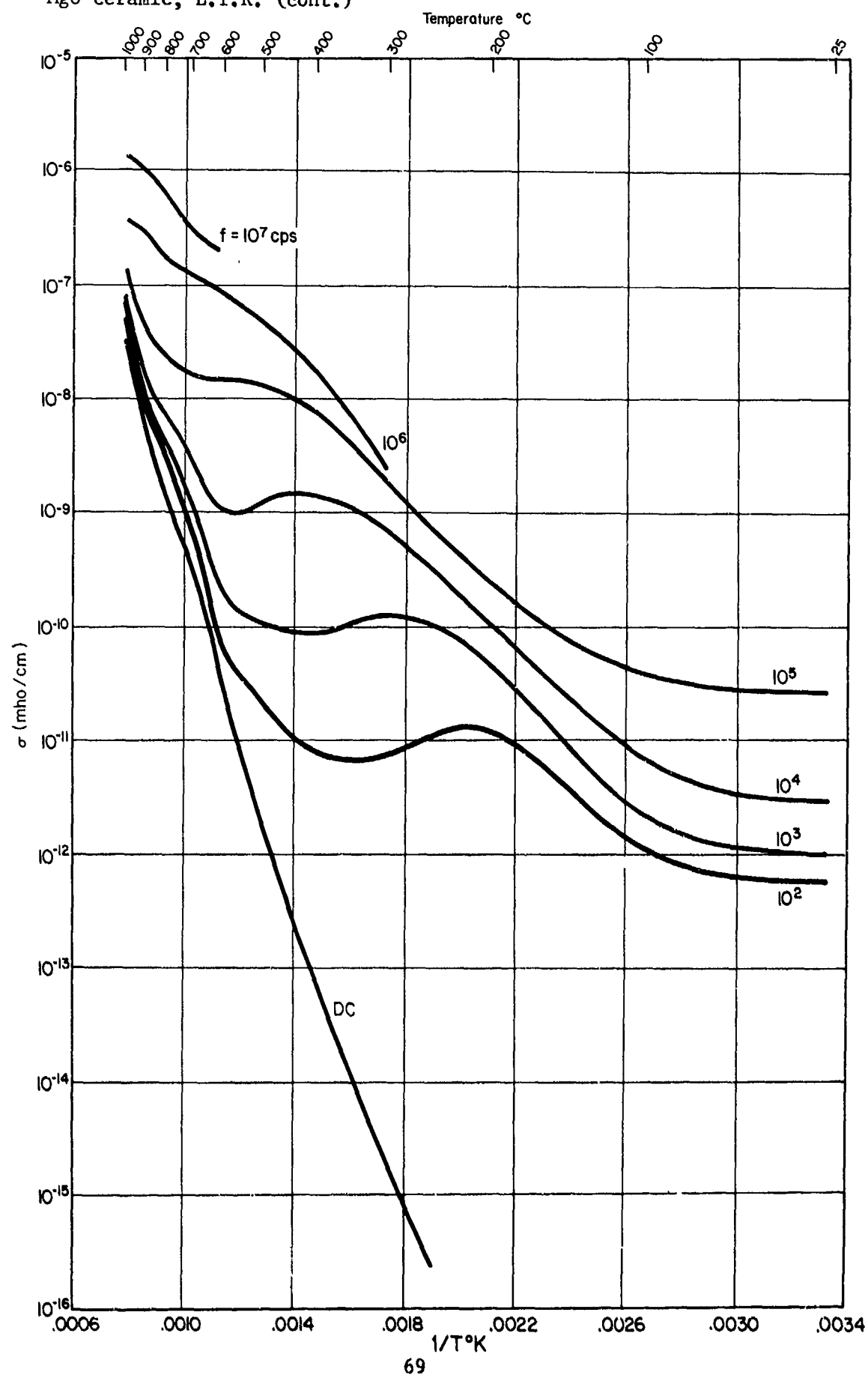
$\tan \delta \times 10^{-4}$   
0.3

MgO ceramic

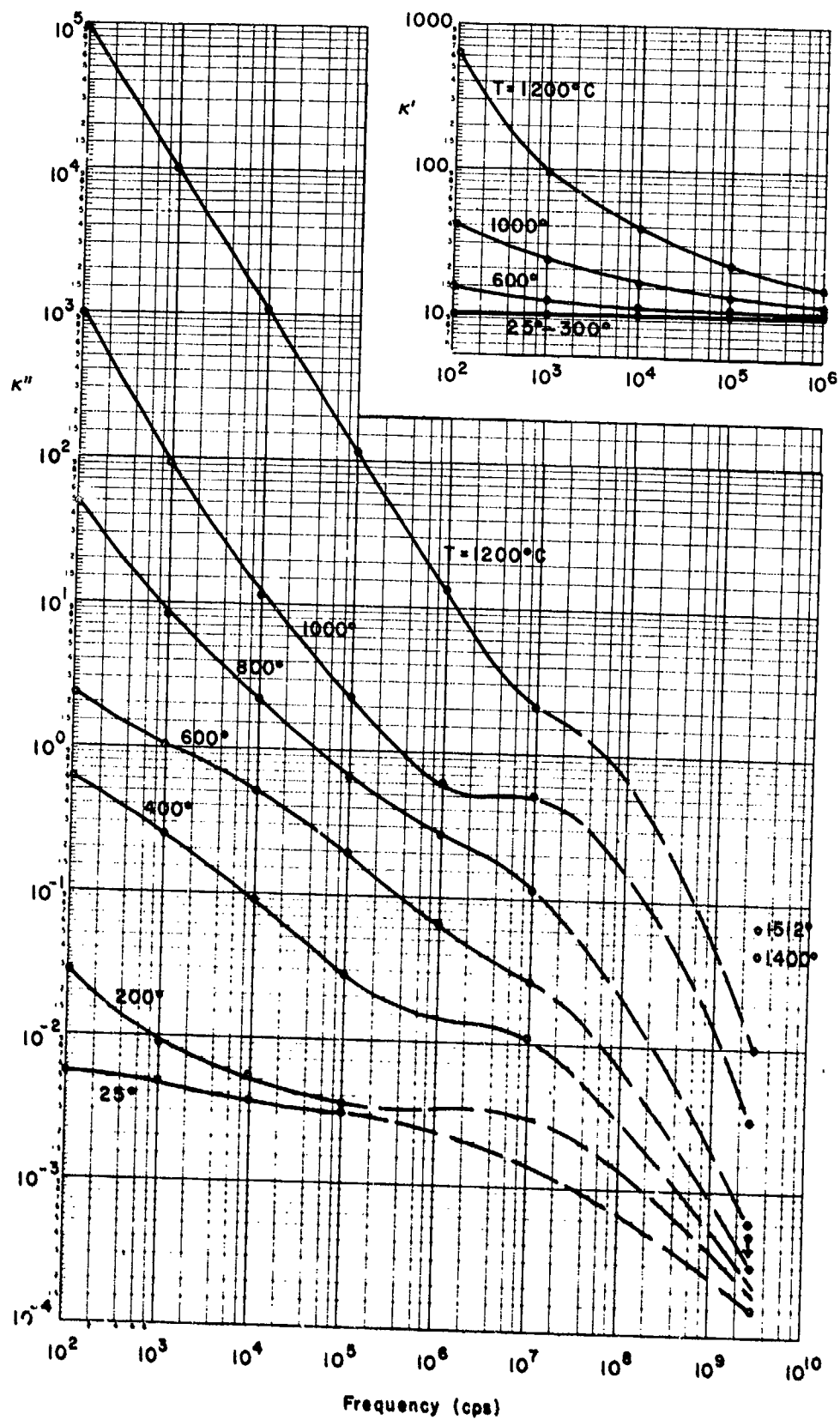
Laboratory for Insulation Research  
Density 3.30 g/cm<sup>3</sup>



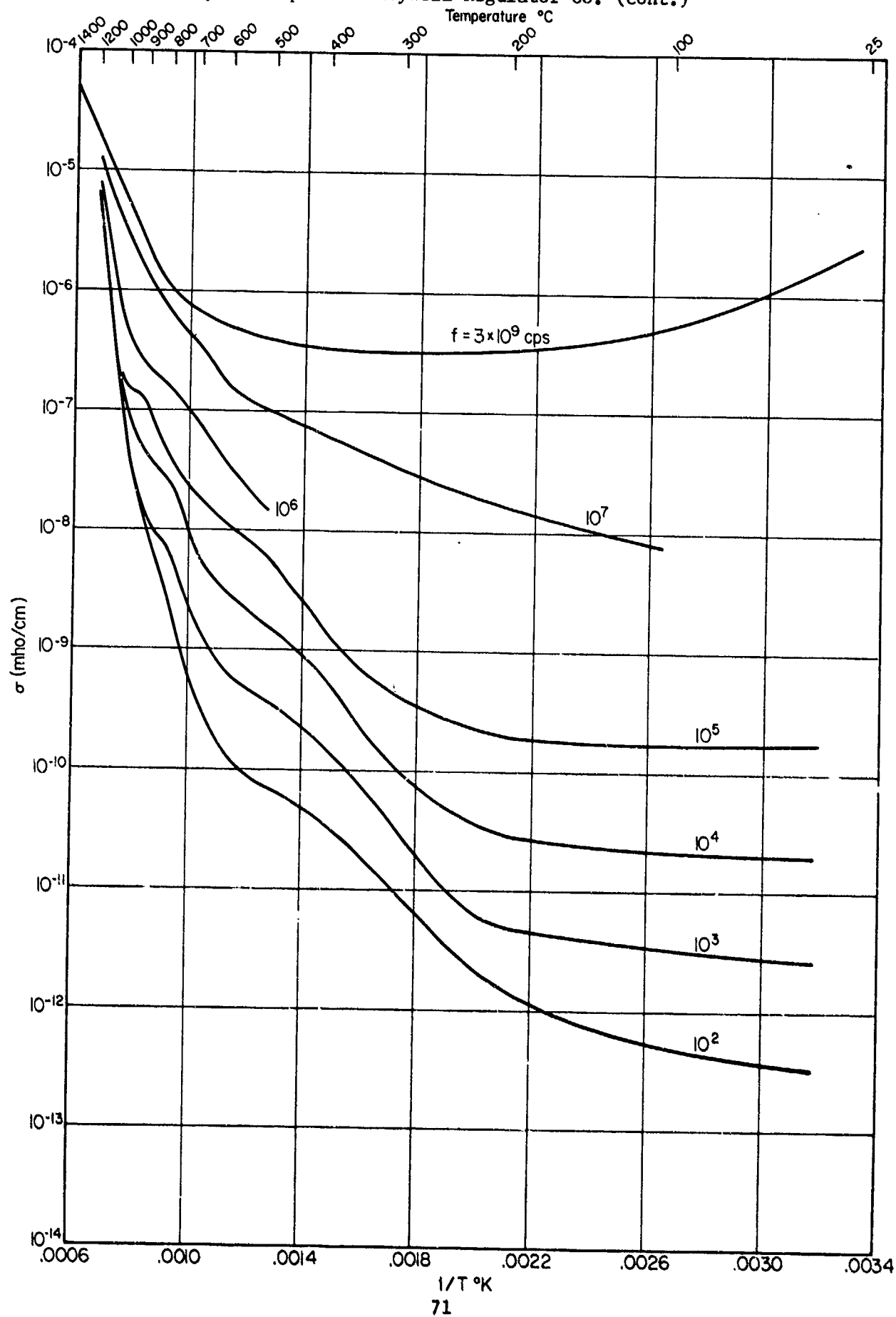
MgO ceramic, L.I.R. (cont.)



MgO ceramic, Minneapolis Honeywell Regulator Co., 99.95% MgO,  
density 3.52 g/cc.



MgO ceramic, Minneapolis Honeywell Regulator Co. (cont.)



Magnesium metasilicate,  
multicrystalline, F-66

Bell Telephone Laboratories

14 GHz

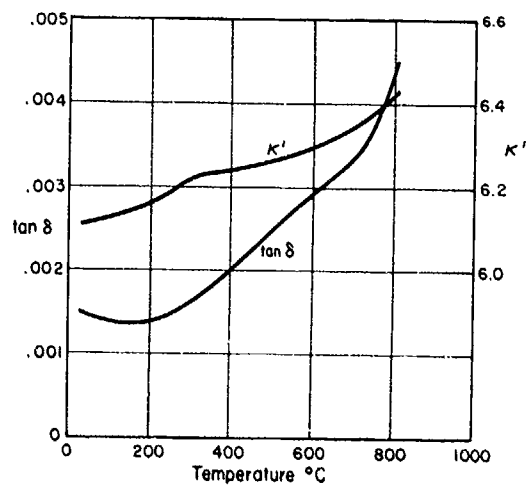
T °C	$\kappa'$	$\tan \delta$
25	6.37	.0012
100	6.39	.0012
200	6.43	.0012
300	6.47	.0012
400	6.52	.0013
500	6.58	.0015
600	6.67	.0020
700	6.75	.0047
800	6.85	.0165

50 GHz

25	6.25	.0012
----	------	-------

International Pipe and Ceramic Corp.  
(Gladding McBean and Co.)

Steatite TC-503, 8.52 GHz



## Magnesium orthosilicate, multicrystalline

General Electric  
Electronic Components Div.

F-118

Density: disk 3.087, cylinder 3.071 g/cm<sup>3</sup>

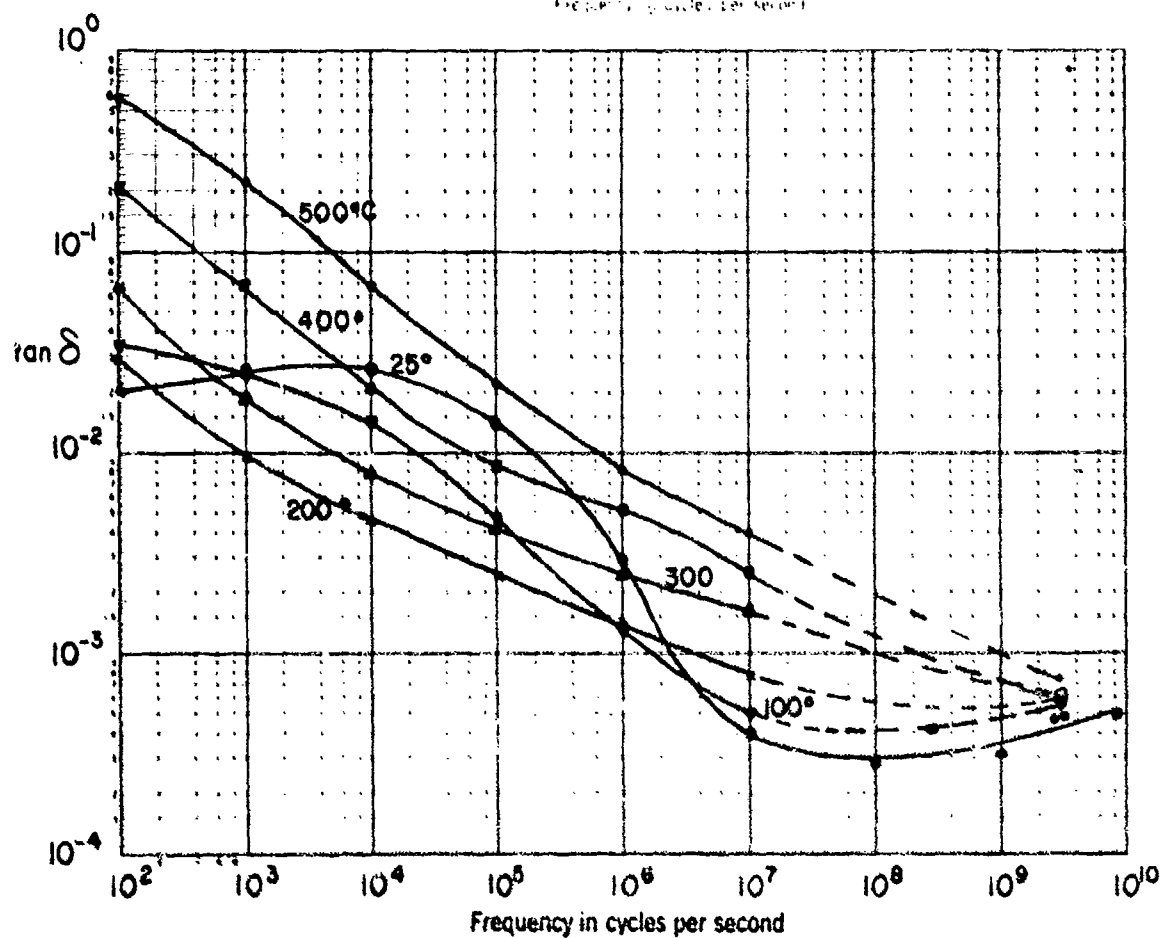
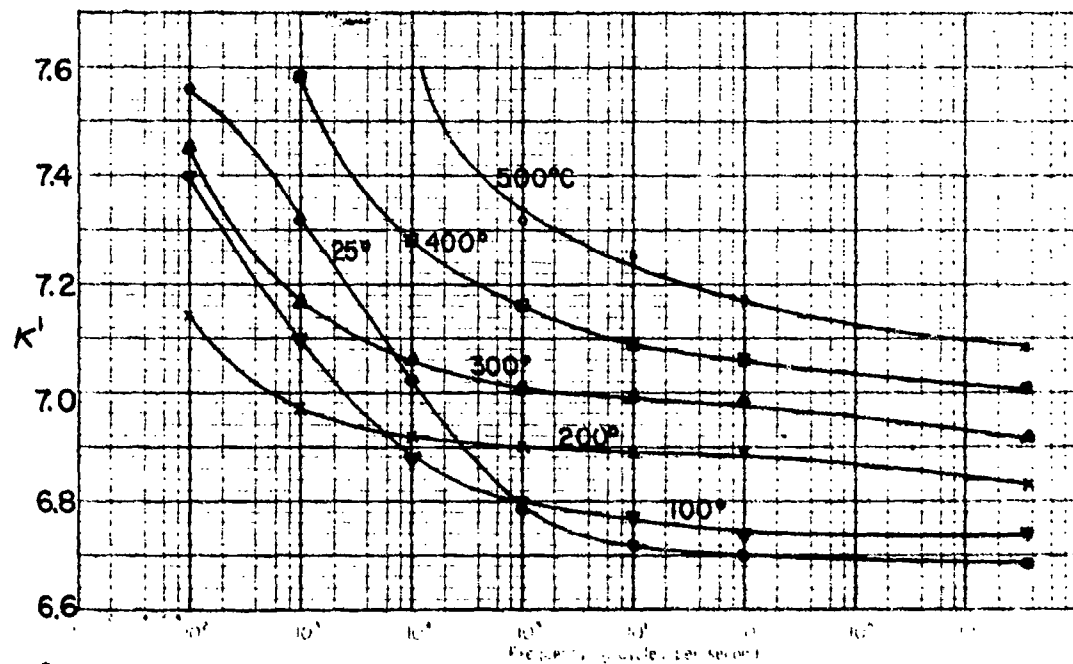
Freq. Hz	25°C		100°C		200°C		300°C		400°C		500°C		550°C	
	$\kappa$	$\tan \delta$	$\kappa$	$\tan \delta$	$\kappa$	$\tan \delta$	$\kappa$	$\tan \delta$	$\kappa$	$\tan \delta$	$\kappa$	$\tan \delta$	$\kappa$	$\tan \delta$
10 <sup>2</sup>	6.625	.00098	6.70	.00445	6.80	.00134	6.91	.00636	7.23	.0662	8.78	.421		
10 <sup>3</sup>	6.62	.00027		.00065	6.79	.00076	6.89	.00198	7.04	.0127	7.44	.0890		
2x10 <sup>3</sup>				.00086										
3x10 <sup>3</sup>				.00098	6.78	.00057								
4x10 <sup>3</sup>				.00108										
5x10 <sup>3</sup>				.00110										
6x10 <sup>3</sup>				.00107										
8x10 <sup>3</sup>				.00102										
10 <sup>4</sup>	6.62	.00013	6.70	.00090	6.78	.00044	6.88	.00090	6.98	.00334	7.20	.0188		
10 <sup>5</sup>	6.62	.000110	6.69	.00024	6.78	.00064	6.87	.00051	6.96	.00123	7.14	.0049		
5x10 <sup>5</sup>					6.77	.00098								
10 <sup>6</sup>	6.62	.000072	6.69	.00016	6.77	.00074	6.85	.00046	6.96	.00069	7.09	.00329		
10 <sup>7</sup>	6.62	.00011	6.69	.00024	6.77	.00025	6.84	.00083	6.95	.00023	7.08	.00149		
10 <sup>8</sup>														
8.5 x 10 <sup>9</sup>	6.59	.00083	6.64	.00086	6.73	.00092	6.81	.00100	6.90	.00109	6.98	.00119	7.03	.00124
1.4x10 <sup>10</sup>														
2.4x10 <sup>10</sup>														

F-202

Freq. Hz	25°C		100°C		200°C		300°C		400°C		500°C		550°C	
	$\kappa$	$\tan \delta$	$\kappa$	$\tan \delta$	$\kappa$	$\tan \delta$	$\kappa$	$\tan \delta$	$\kappa$	$\tan \delta$	$\kappa$	$\tan \delta$	$\kappa$	$\tan \delta$
10 <sup>2</sup>	6.77	.000515	6.86	.00107	6.99	.00277	7.26	.02835	9.74	.508	14.73	4.29		
10 <sup>3</sup>	6.76	.000293	6.85	.00063	6.98	.00202	7.14	.0076	7.70	.142	10.08	.822		
10 <sup>4</sup>	6.76	.000240	6.84	.00056	6.96	.00124	7.08	.0037	7.34	.0293	8.13	.178		
10 <sup>5</sup>	6.76	.000233	6.83	.00035	6.95	.00077	7.06	.0017	7.22	.00705	7.40	.0474		
10 <sup>6</sup>	6.76	.000245	6.83	.00032	6.94	.00067	7.06	.00120	7.18	.0025	7.31	.00975		
10 <sup>7</sup>	6.76	.00025	6.83	.00025	6.94	.00052	7.05	.00098	7.15	.00153	7.28	.00394		
10 <sup>8</sup>														
8.5x10 <sup>9</sup>	6.74	.00080	6.81	.00090	6.92	.0015	7.02	.0014	7.13	.0019	7.23	.0027	7.28	.0031
1.4x10 <sup>10</sup>														
2.4x10 <sup>10</sup>														

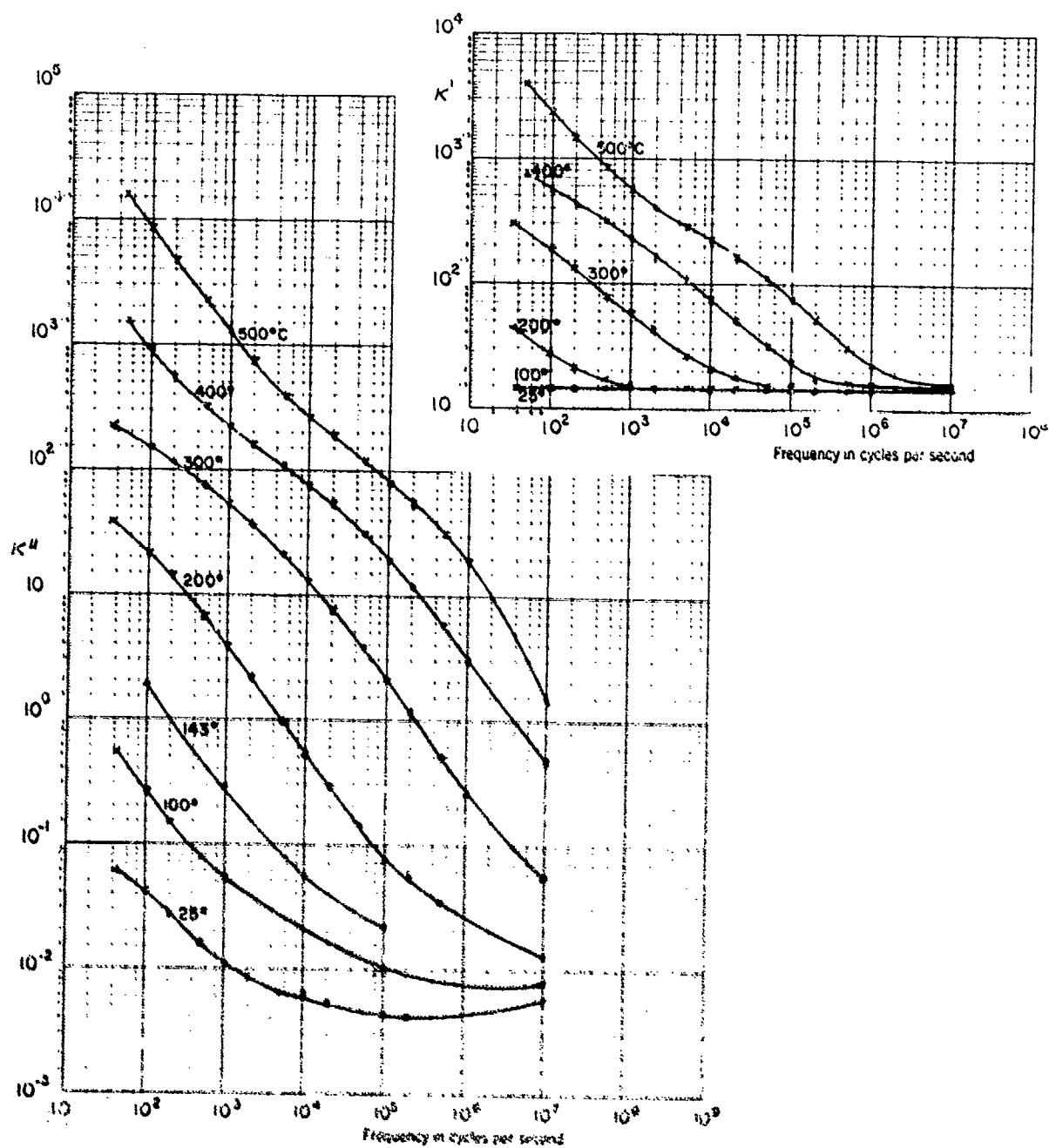
Density of disk 3.087, cylinder 3.086 g/cm<sup>3</sup>





Magnesium titanate ( $\text{MgTiO}_3$ )  
Density  $3.21 \text{ g/cm}^3$

U. S. Sonics



Manganese fluoride crystal ( $\text{MnF}_2$ )

Columbia University

$f$  (Hz)       $K'$        $\tan \delta$

$10^3$        $7.2 \pm .2$       .043

$10^7$        $6.7 \pm .2$        $< .004$

$E \perp$  to platelike, unoriented crystal

Mercury compounds, hot-pressed

Theor. density	Compound	Sample No.	Density (g/cm <sup>3</sup> )	T°C	$10^2$	$10^3$	$10^4$	$10^5$	$10^6$	$10^7$	$8.5 \times 10^9$
6.27	HgI <sub>2</sub>	1	-	25	$\kappa$	13.7			11.8		13.4
					$\tan \delta$	.191			.0034		.0037
		2	5.48	25	$\kappa$	14.3			12.57		
					$\tan \delta$	.208			.0026		
		3	5.69	25	$\kappa$						13.9
					$\tan \delta$						< .003
		4	5.56	25	$\kappa$	16.11	13.15	12.41	12.39	12.38	12.37
					$\tan \delta$	.828	.154	.0268	.00427	.00117	.00043
				50	$\kappa$	44.35	16.87	13.50	12.98	12.90	12.85
					$\tan \delta$	2.33	.888	.168	.0264	.0047	.00095
				25	$\kappa$	15.45	13.03	12.45	12.42	12.41	12.40
					$\tan \delta$	.713	.185	.0334	.0057	.00149	.00076
7.15	HgCl	1	5.36	25	$\kappa$	7.49	7.48	7.48	7.46	7.45	
					$\tan \delta$	.0013	.00044	.00029	.00034	.00040	.00029
				50	$\kappa$	7.62	7.61	2.59	7.58	7.57	7.57
					$\tan \delta$	.00328	.00005	.00046	.00021	.00028	.00039
				25	$\kappa$	7.58	7.58	7.57	7.57	7.56	7.56
					$\tan \delta$	.00050	.00027	.00018	.00021	.00034	.00046
7.73	HgS	1	5.19	25	$\kappa$	9.75	9.72	9.68	9.64	9.62	9.58
					$\tan \delta$	.0036	.0035	.0029	.0021	.0017	.0011
				50	$\kappa$	9.64	9.61	9.58	9.56	9.53	9.49
					$\tan \delta$	.00324	.00225	.00188	.00174	.00181	.00144
				25	$\kappa$	9.63	9.62	9.62	9.61	9.58	9.57
					$\tan \delta$	.00207	.00177	.00162	.00165	.00147	.00119

Nickel oxide, NiO, single crystal

M. I. T., Crystal Physics Lab.

At 25°C, 1 MHz

$\kappa' = 11.9$

$\tan \delta = .0154$

For complete data see: K. V. Rao and A. Smakula, J. Appl. Phys. 36, 2031-2038 (1965).

Phosphate glass

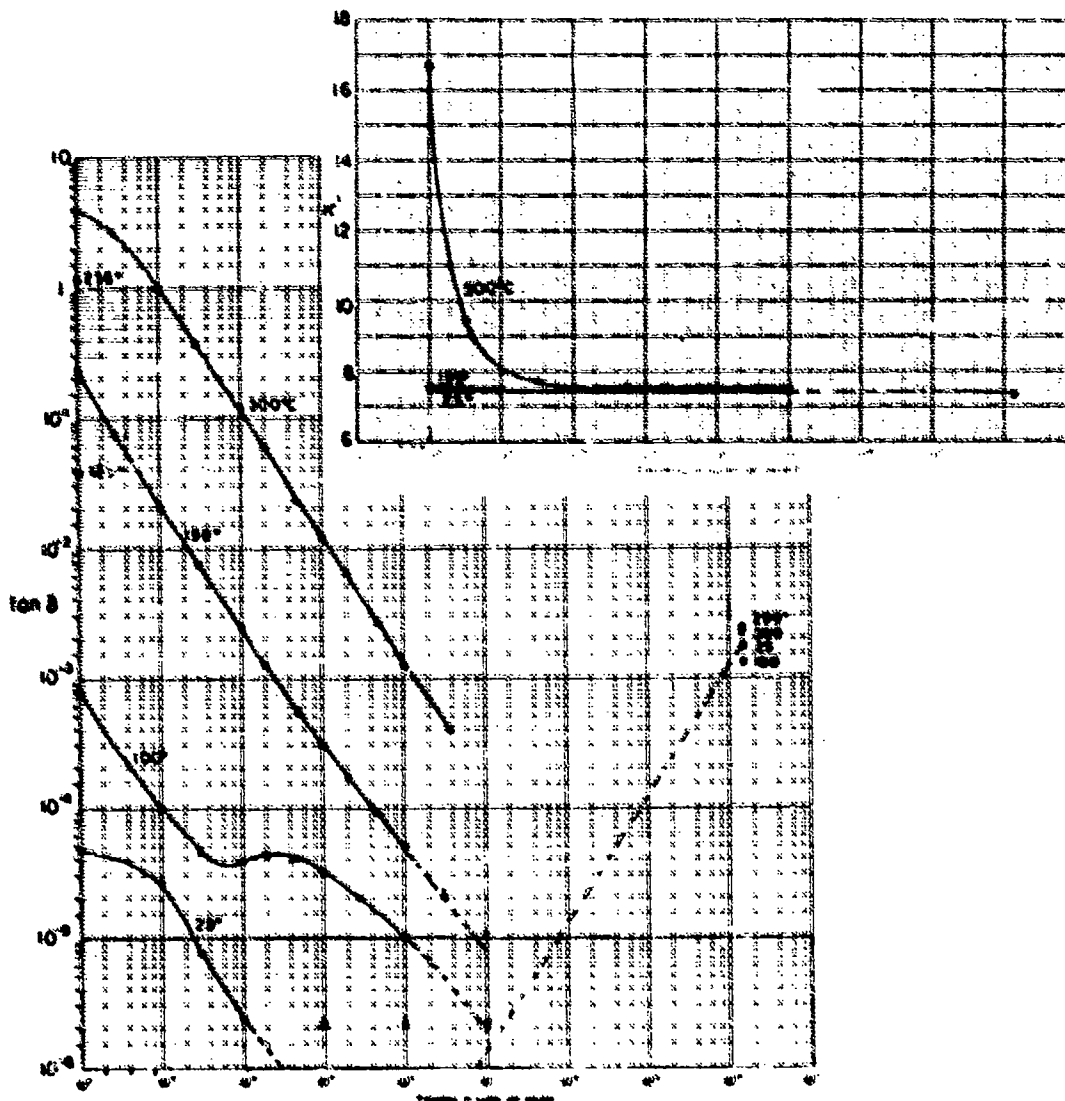
American Optical

50 GHz

	$\kappa'$	$\tan \delta \times 10^{-4}$
2043X	5.00	52
2273X	4.74	26

Rubidium manganese fluoride

Massachusetts Institute of Technology  
Crystal Physics Laboratory

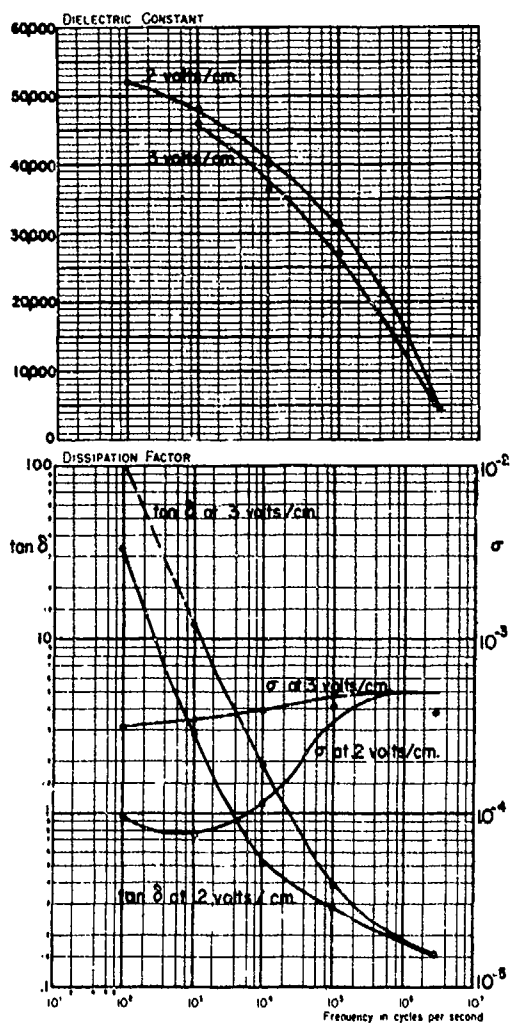


Silicon crystal, undoped

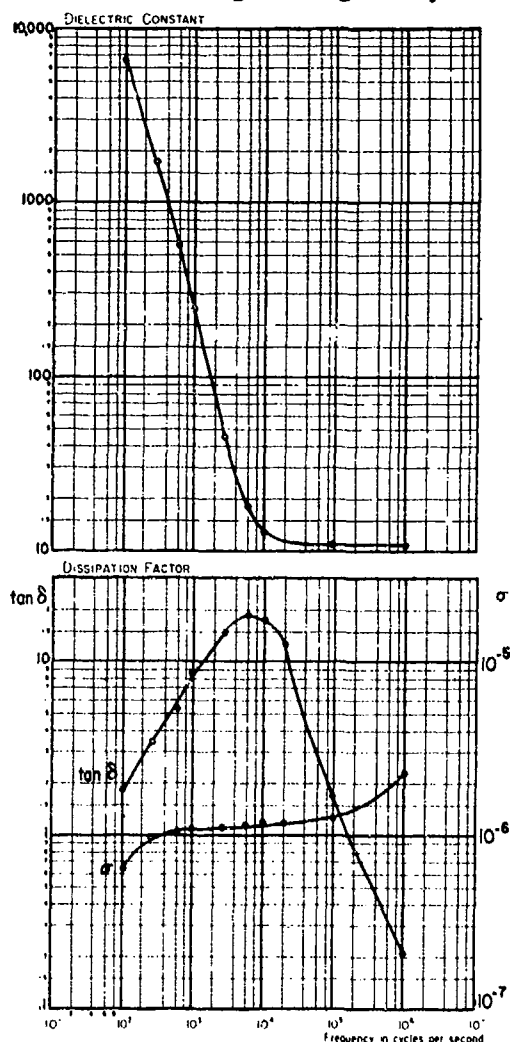
Brown University

Apparent properties of 1 cm cube sample with  
evaporated gold electrodes.

Silicon single crystal



Radiation damaged single crystal



Silicon crystal, intrinsic  
at 25°C

M. I. T., Crystal Physics Lab.

f (Hz)	$\kappa'$	$\tan \delta$	$\rho$ (ohm-cm)
$10^3$	-	-	4100
$1.4 \times 10^{10}$	12.0	.0090	1190

# Silicon carbide type attenuator materials

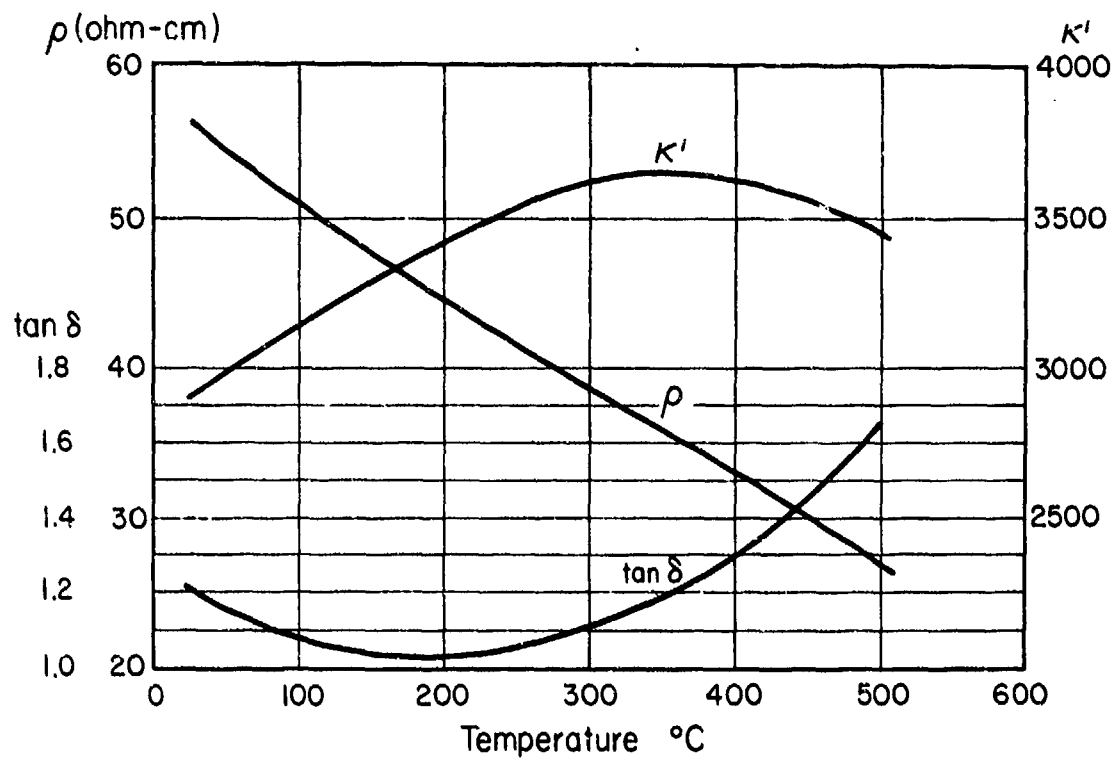
# Carborundum

Nominal resistivity (ohm-cm)	Temperature (°C)	f (Hz)	$\kappa'$	$\tan \delta$	Measured resistivity (ohm-cm)
35	25	$3 \times 10^8$	167	0.96	37.2
	25	$10^9$	107	0.686	24.4
	25	$3 \times 10^9$	60	0.58	17.2
	25	$8.5 \times 10^9$	47.7	0.55	8.05
0.1	25	$8.5 \times 10^9$	2130	1.85	0.069
50	25*	$10^6$	10,150	1.17	151
	25**	$10^6$	29,450	1.36	45
	25*	$10^7$	2810	1.21	56.5

\* Two-terminal measurement.

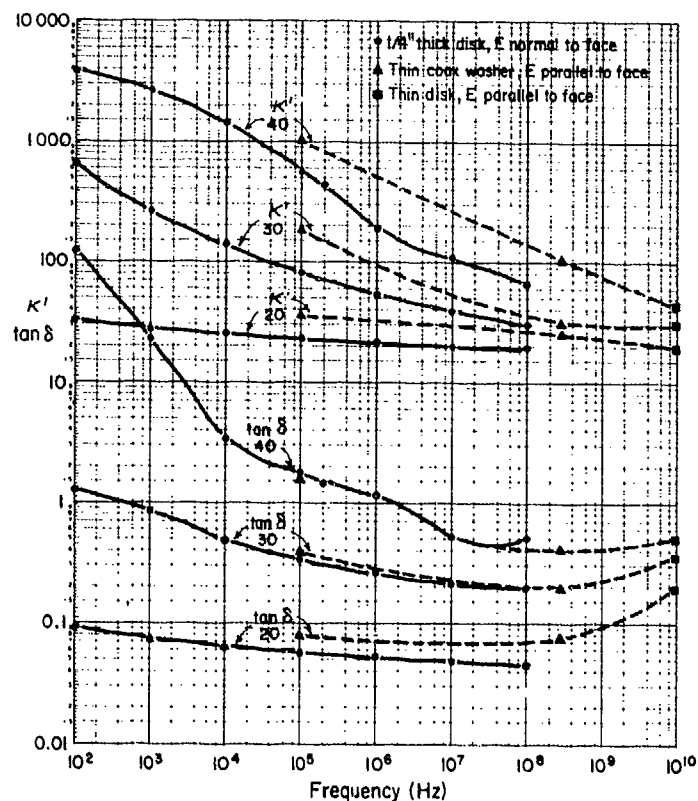
\*\* Four-terminal measurement, different sample

Nominal 50-ohm material at  $10^7$  Hz



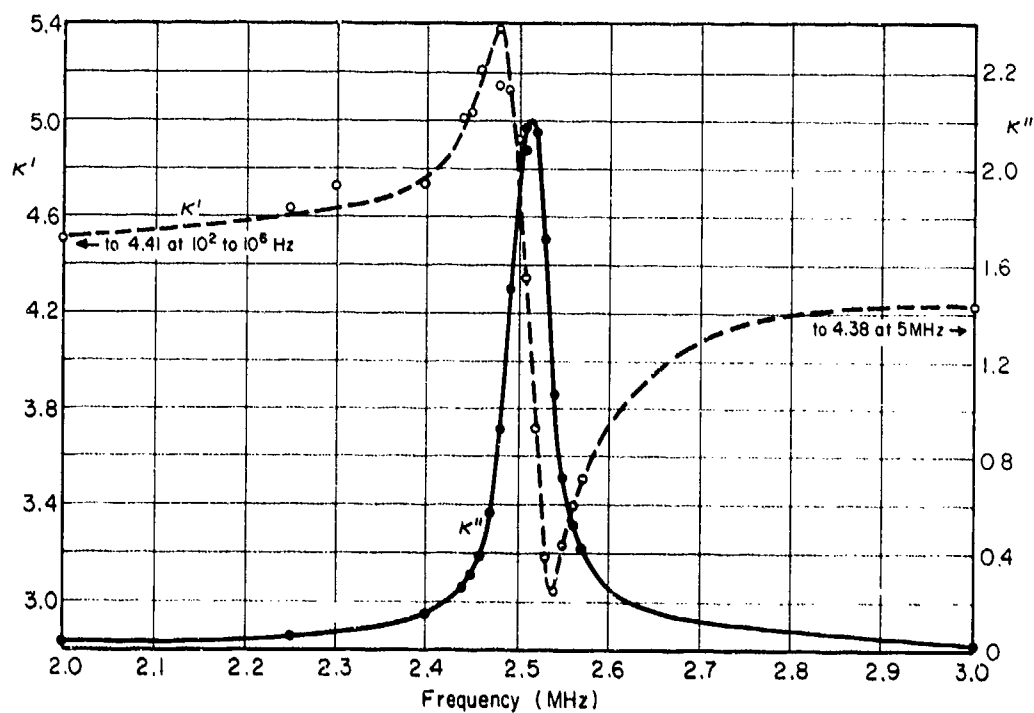
Carberlox 20, 30, 40  
BeO and silicon carbide ceramic

National Beryllia Corp.



Silicon dioxide, natural quartz crystal,  
Y-cut plate, silver paint electrodes, at 25°C

Fort Monmouth



# Quartz, continued

Y-cut plate

At 25°C,  $\kappa' = 4.40$

$$1/\kappa' \left( \frac{d\kappa'}{dt} \right) = -2.8 \times 10^{-5} / ^\circ\text{C}$$

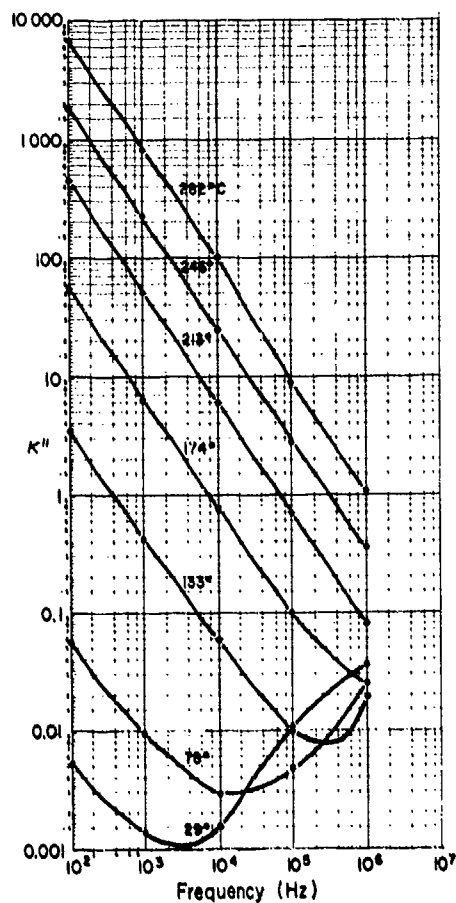
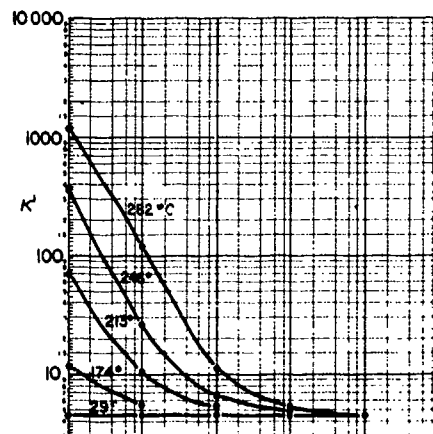
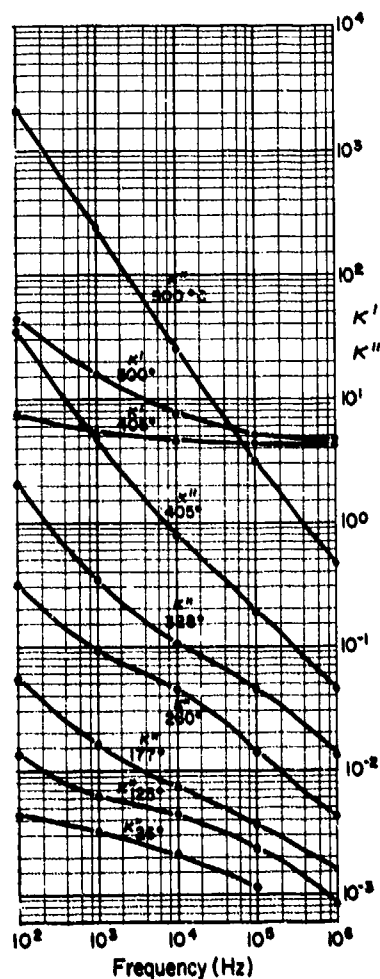
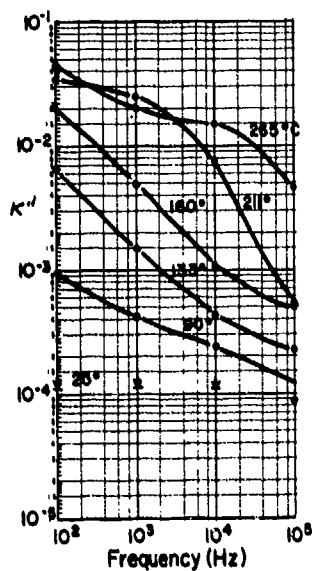
Z-cut plate, E || optic axis

At 25°C,  $\kappa' = 4.64$

$$1/\kappa' \left( \frac{d\kappa'}{dt} \right) = -3.9 \times 10^{-5} / ^\circ\text{C}$$

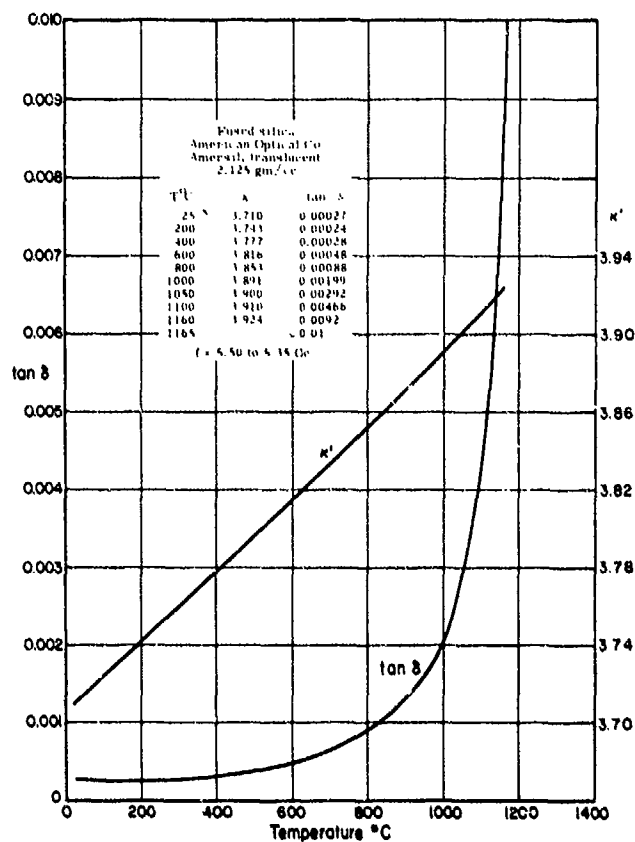
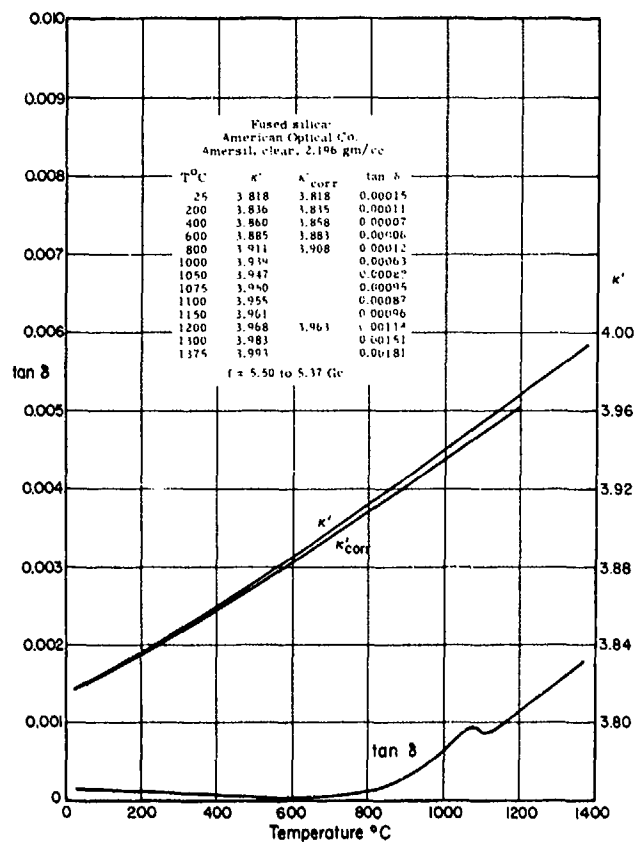
## Silver electrodes

## Pt electrodes



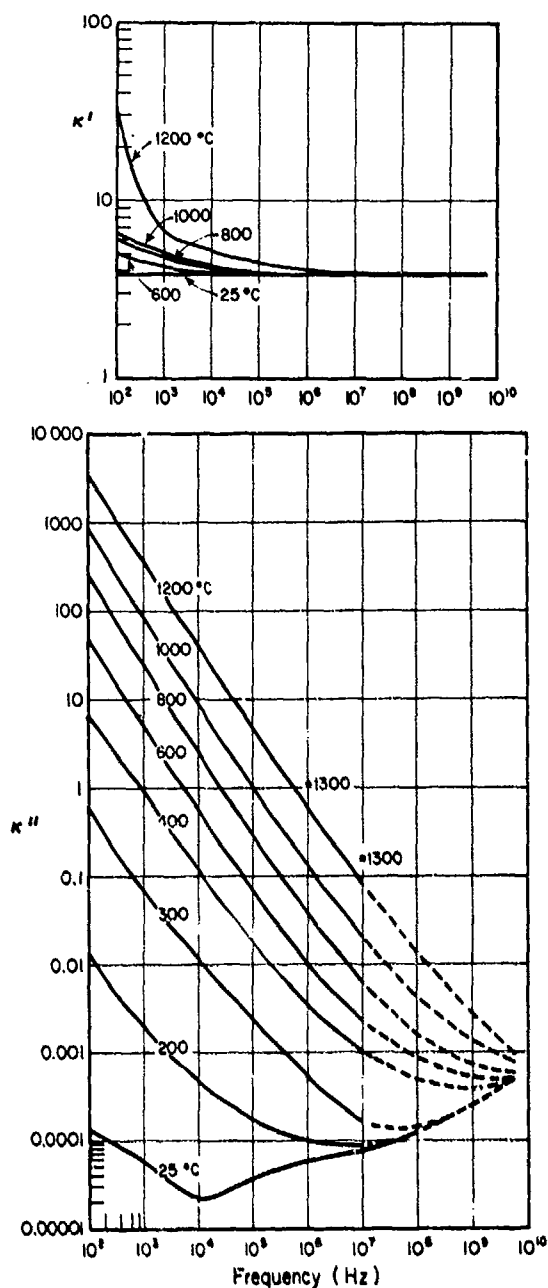


# Silicon dioxide Glasses



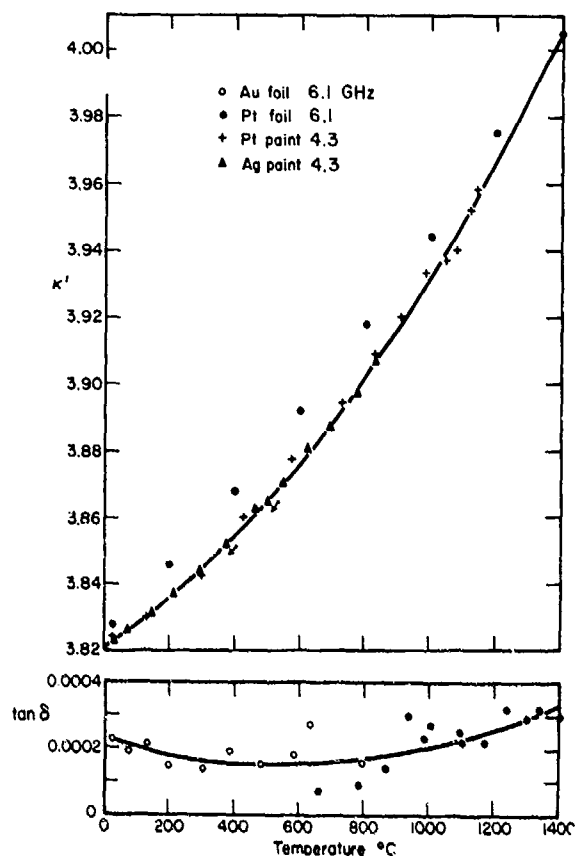
# Silicate glasses

## Fused silica, Corning 7940

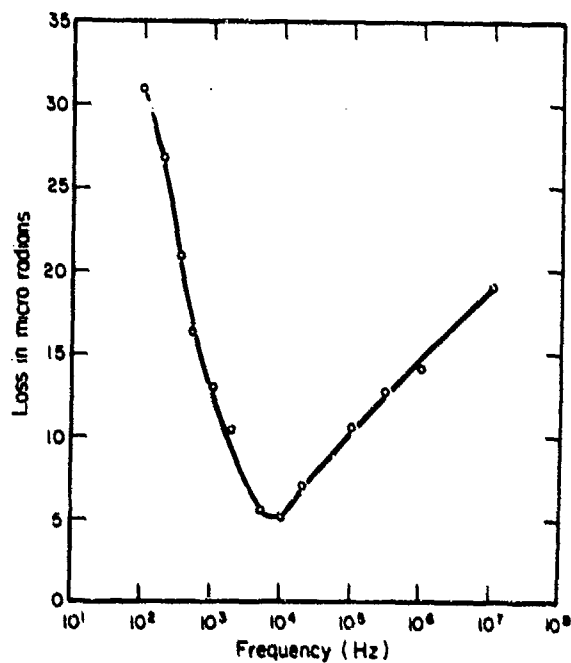


# Corning Glass Works

Microwave data on fused silica, Corning 7940, density = 2.20027 g/cm<sup>3</sup>. Data with foil taken on one sample at 6.1 GHz, data with paint taken on second sample at 4.3 GHz.

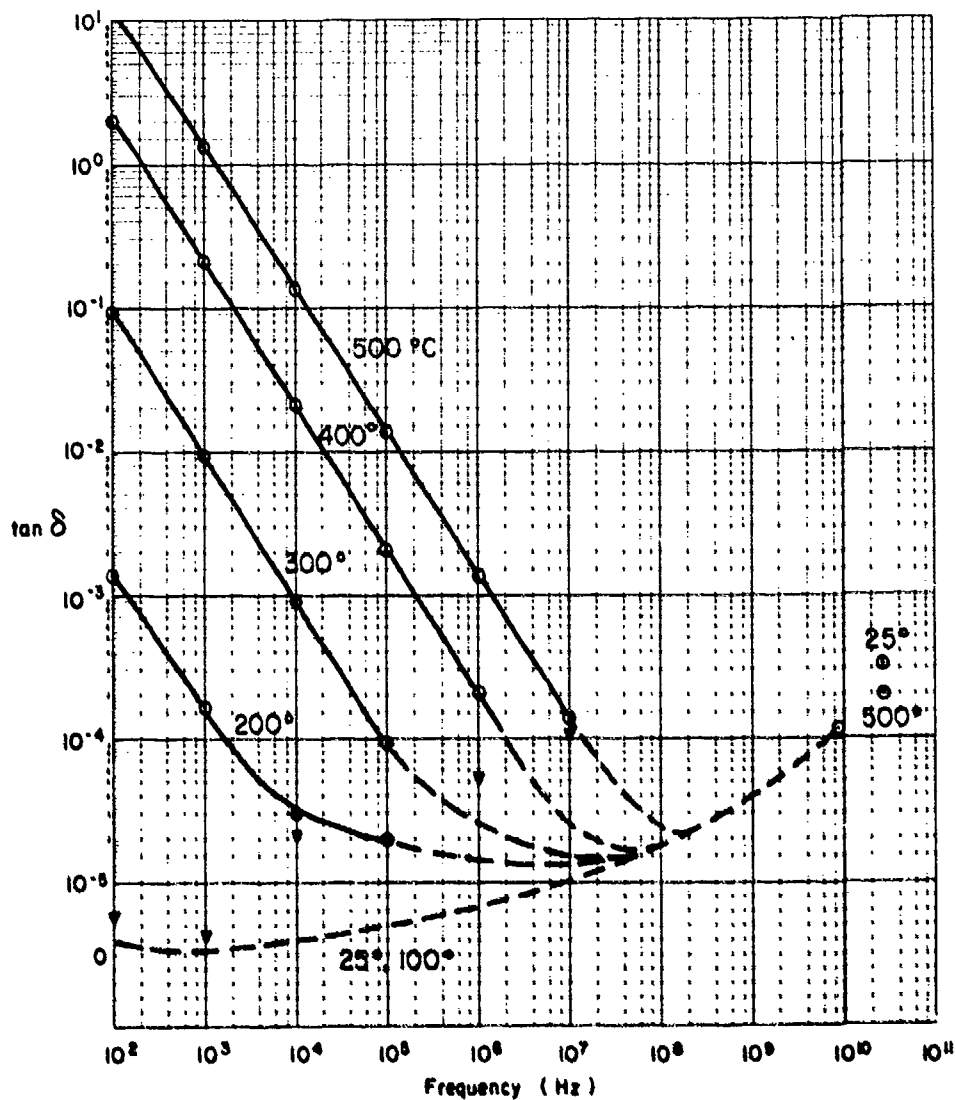
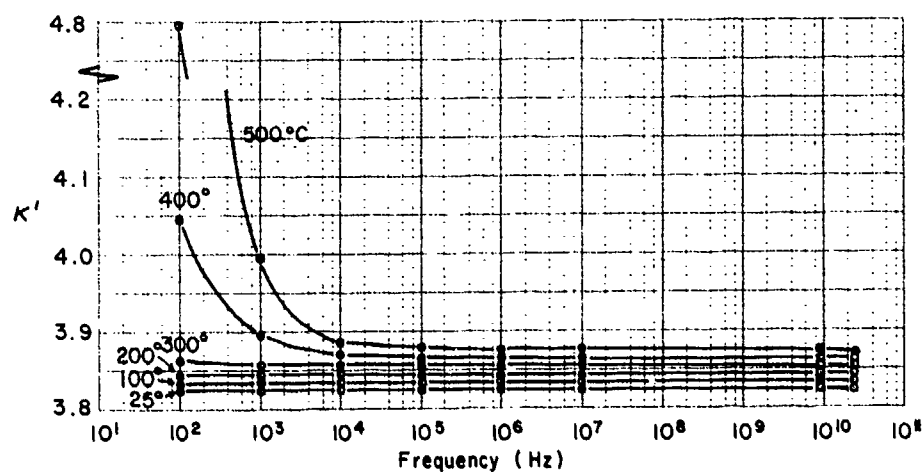


# Corning 7940 continued



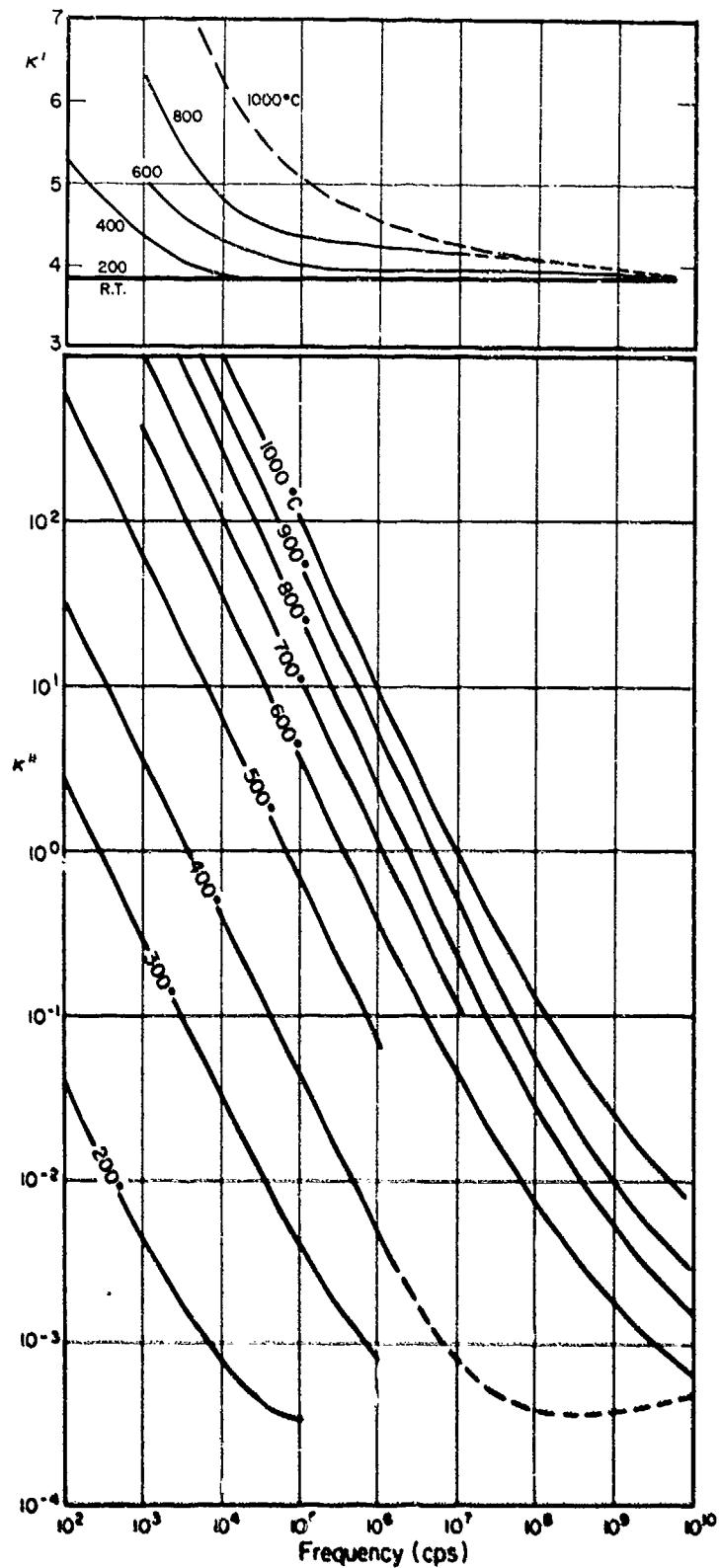
Silicon dioxide, high purity glasses  
Dynasil 4000

Dynasil Corporation of America  
Berlin, New Jersey 08009



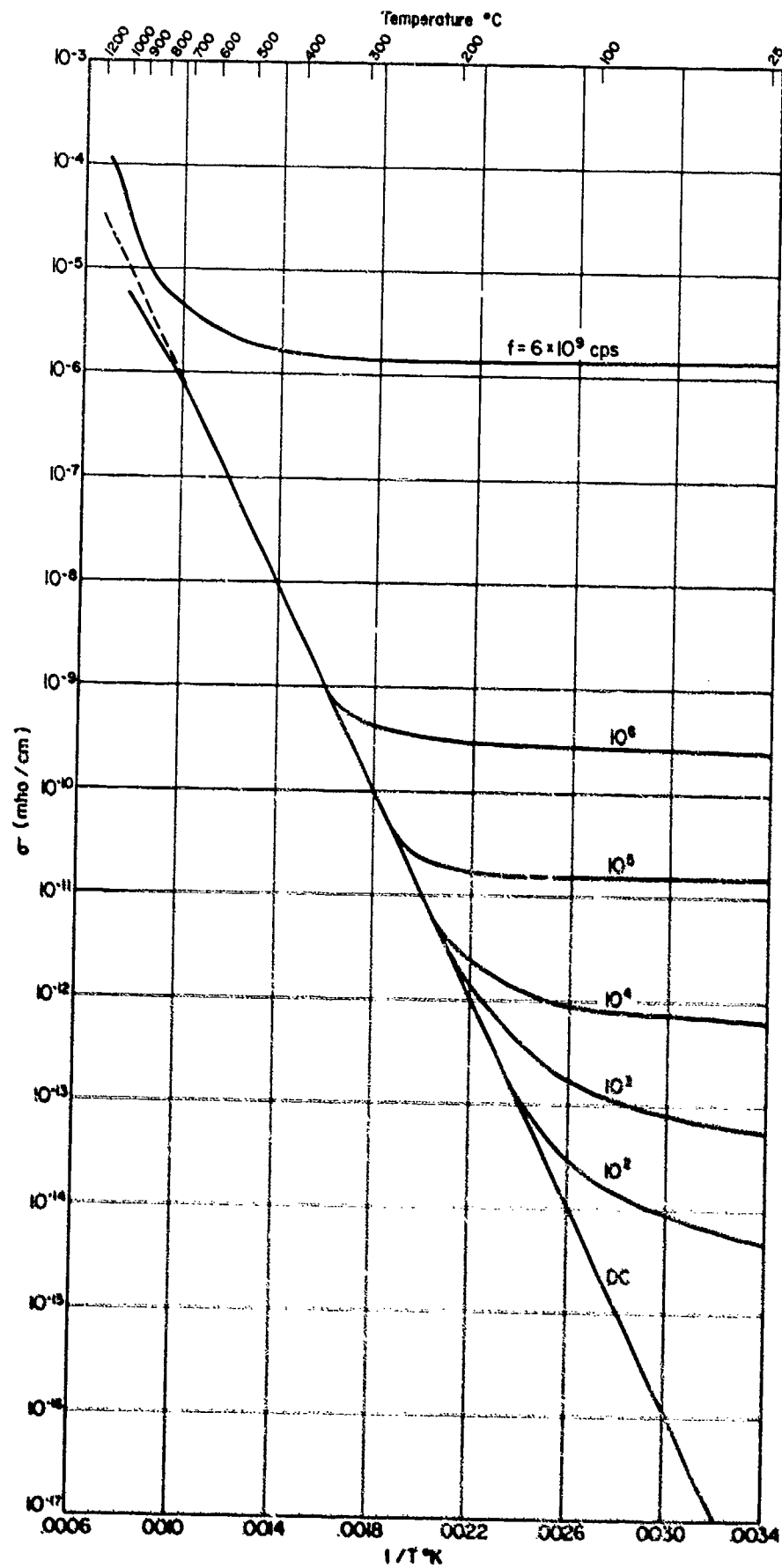
SiO<sub>2</sub>, glass, Type 101 clear, fused quartz,  
99.97 to 99.98% SiO<sub>2</sub>

General Electric  
Silicon dioxide Dept.

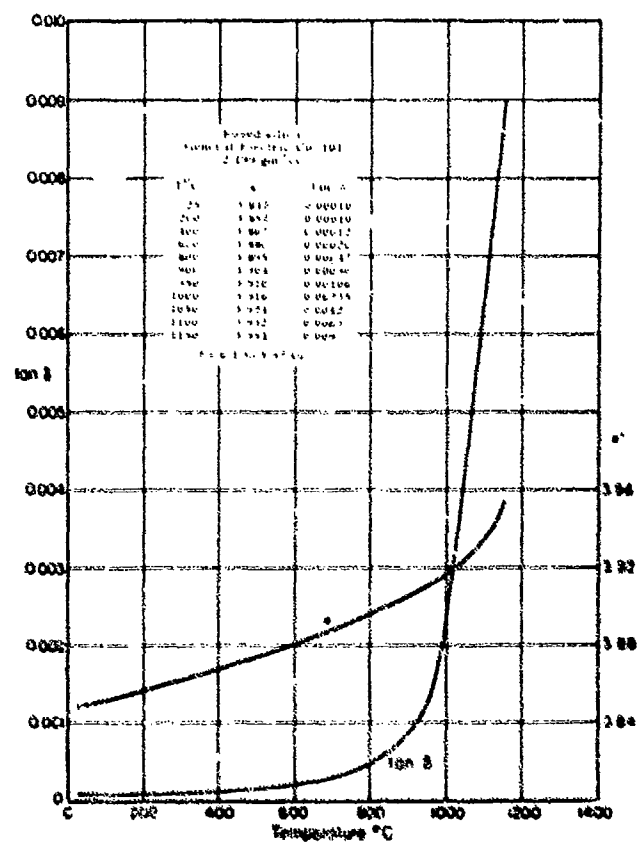


At 50 GHz, 25°C,  $\kappa' = 3.80$ ,  $\tan \delta = 0.0002$

SiO<sub>2</sub>, glass (cont.)



# Silicon dioxide (cont.)



Silicon dioxide, high-purity glasses (cont.)

Spectrosil A

Thermal American Fused Quartz Co.  
Montville, N.J. 07045

25°C, 8.52 GHz:  $\kappa' = 3.826 \pm .003$

$10^4 \tan \delta = 1.9 \pm .4$

Spectrosil B

25°C, 8.52 GHz:  $\kappa' = 3.825 \pm .003$

$10^4 \tan \delta = 1.5 \pm .2$

Frequency in Hz

T°C		$10^2$	$10^3$	$10^4$	$10^5$	$10^6$	$10^7$
25	$\kappa$	3.823	3.823	3.823	3.823	3.823	3.823
	$10^6 \tan \delta$	<4	<4	6	7	<40	<130
100	$\kappa$	3.83	3.83	3.83	3.83	3.83	3.83
	$10^6 \tan \delta$	<4	<4	<8	<10	<40	<130
197	$\kappa$	3.84	3.84	3.84	3.84	3.84	3.84
	$10^6 \tan \delta$	264	44	15	<20	<40	<130
300	$\kappa$	3.86	3.86	3.86	3.86	3.86	3.86
	$10^4 \tan \delta$	151	15.9	2	<.4	<.6	<1.3
398	$\kappa$	3.89	3.86	3.86	3.86	3.86	3.86
	$10^2 \tan \delta$	15.9	1.76	.219	.04	<.02	<.02
486	$\kappa$	3.98	3.89	3.87	3.87	3.87	3.87
	$\tan \delta$	.79	.0883	.00954	.0015	.0005	.0002

Vitreosil, optical grade

25°C, 8.52 GHz,  $\kappa' = 3.811 \pm .005$ ;  $10^4 \tan \delta = 1.17 \pm .2$

Vitreosil, commercial grade

25°C, 8.52 GHz,  $\kappa' = 3.805 \pm .01$ ;  $10^4 \tan \delta = .80 \pm .13$

Mixed silicate glasses

Corning Lab. No. 119BUC  
magnetic glass

Corning Glass Works

25°C, 8.52 GHz

$\kappa'$	$\tan \delta$	$\kappa'_m$	$\tan \delta_m$
20.8	0.157	1.006	0.372

Corning Code 1723 glass

14 GHz

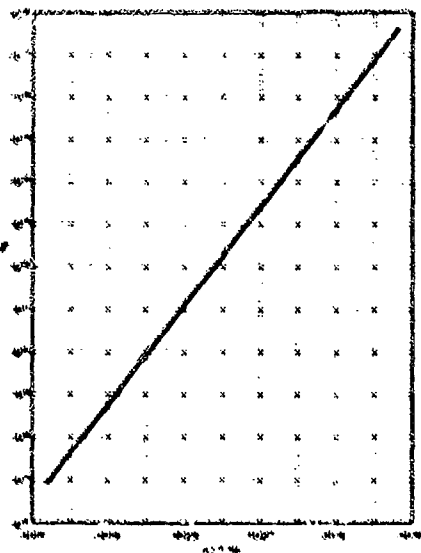
24 GHz

T°C	$\kappa'$	$\tan \delta$	T°C	$\kappa'$	$\tan \delta$
25	6.18	.0069	25	6.13	.0075
85	6.21	.0067	85	6.16	.0075
144	6.24	.0065	155	6.20	.0074
231	6.27	.0063	251	6.24	.0073
305	6.31	.0061	333	6.28	.0074
339	6.33	.0060	419	6.32	.0073
396	6.36	.0059	446	6.35	.0073
464	6.40	.0057	510	6.39	.0074
502	6.43	.0056			

Lancaster

No. 7552

Resistivities measured at 100 Hz



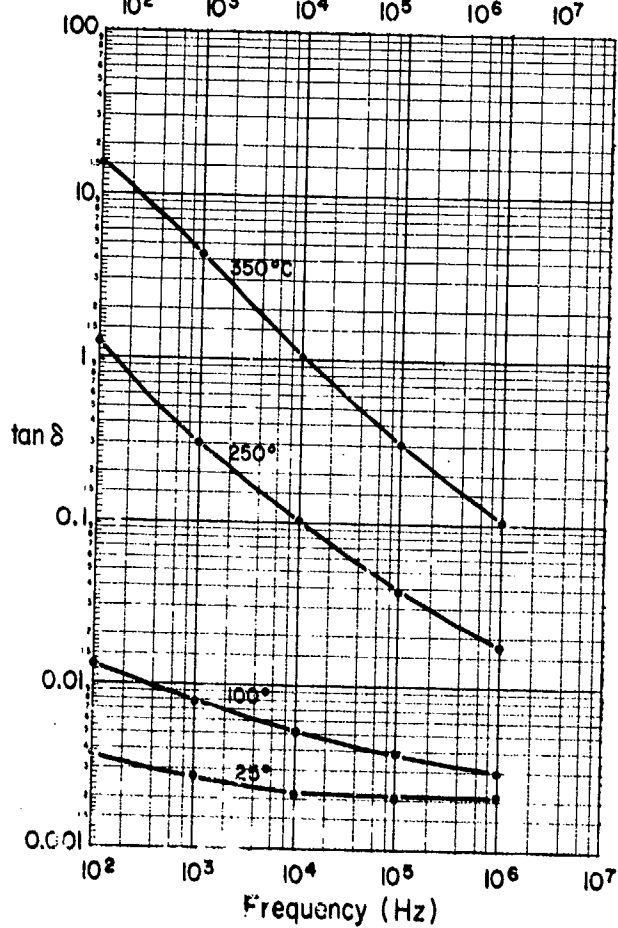
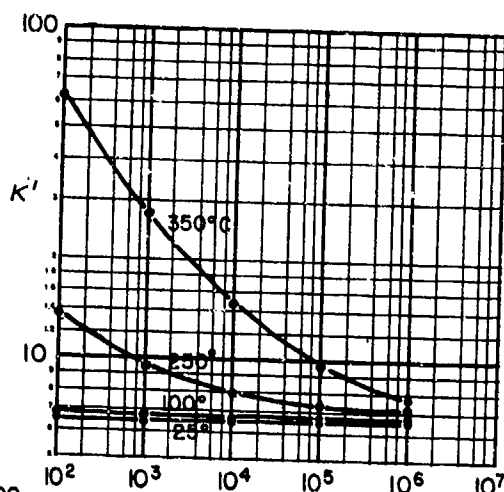


Silica glasses (cont.)

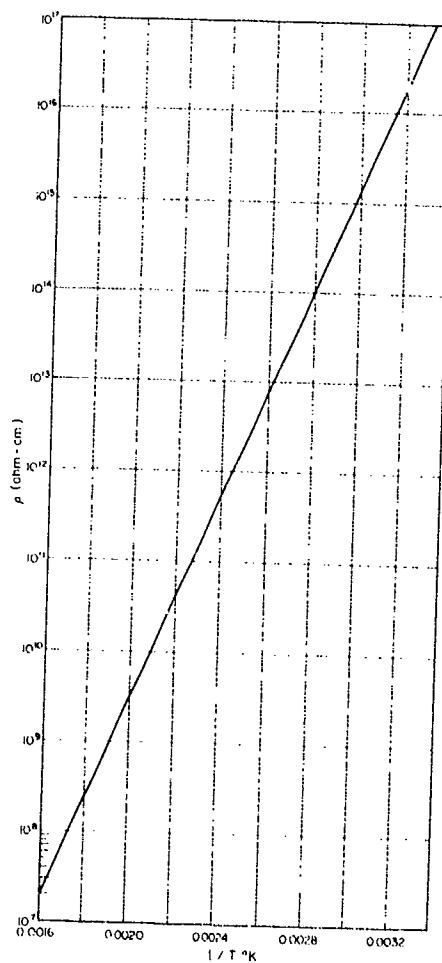
Lancaster

(Mixed silicate glasses), resistivities measured at 100 Hz

7357

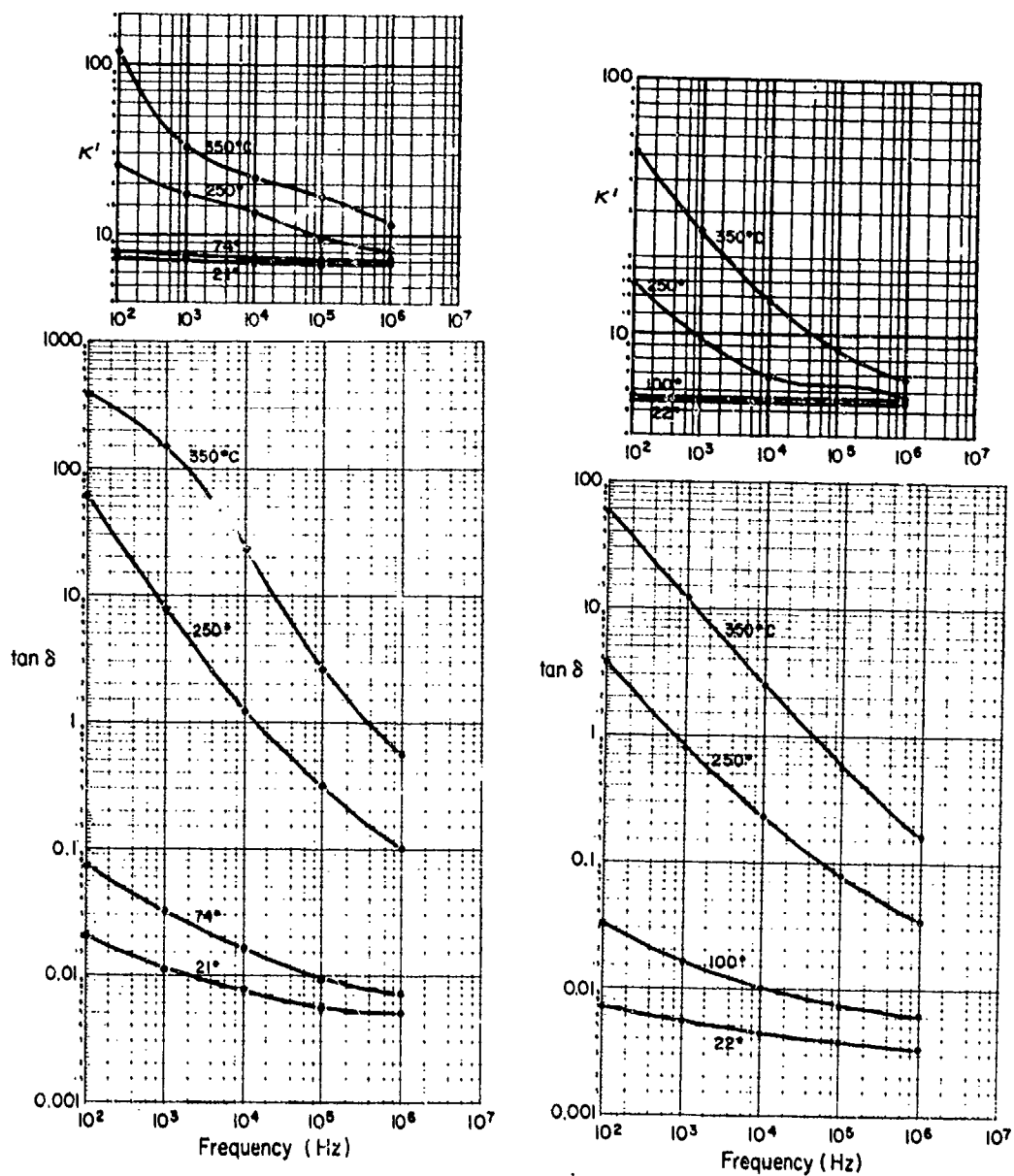


7357



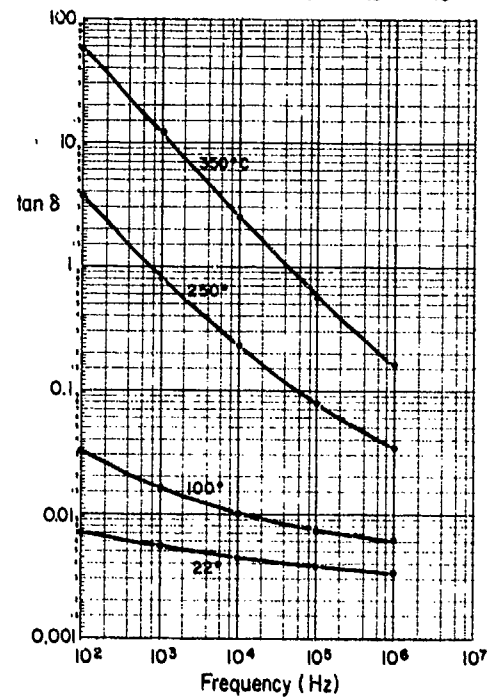
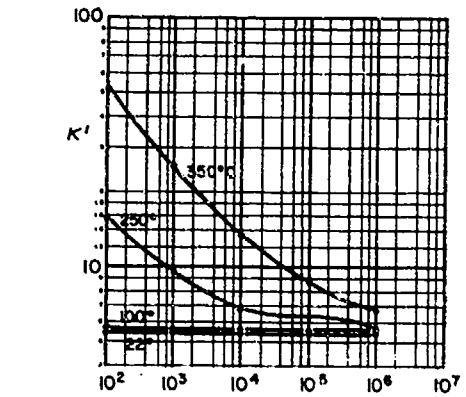
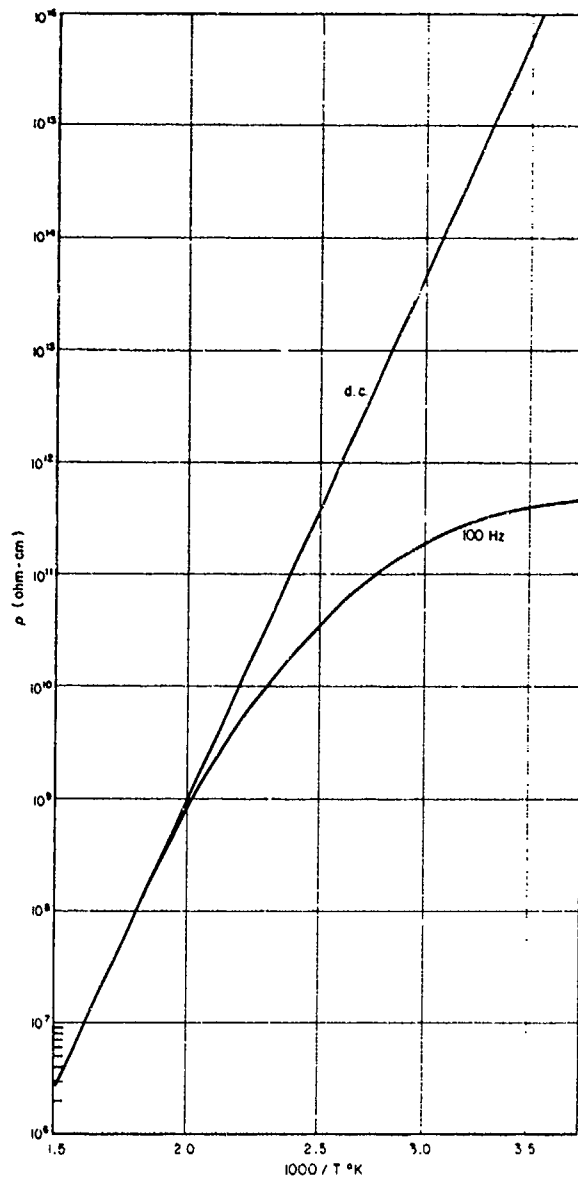
Lancaster glasses (cont.)

L1957



Lancaster glasses (cont.)

No. L 8100



Mixed silicate glasses (cont.)

M.I.T., Laboratory for Insulation Research

Soda silicate glass	50 GHz	
	$\kappa$	$\tan \delta \times 10^{-4}$
1) 9% Na <sub>2</sub> O, 91% SiO <sub>2</sub>	4.90	158
2) 12% Na <sub>2</sub> O, 88% SiO <sub>2</sub>	5.08	178

Sample EE 9

Owens-Illinois  
Toledo, Ohio 43601

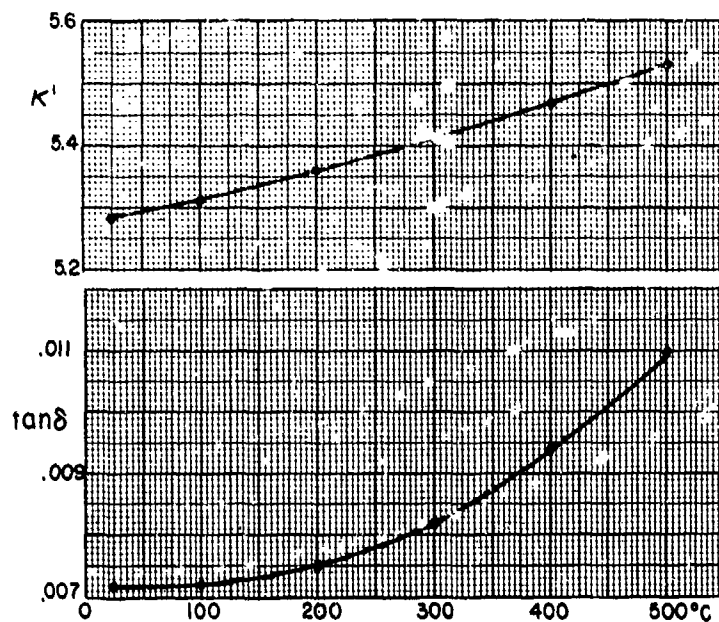
Sample EE 10

EE 9 Freq., 8.52 GHz			EE 10 Freq., 8.52 GHz		
T°C	$\kappa$	$\tan \delta$	T°C	$\kappa$	$\tan \delta$
25	5.84	.0070	25	8.17	.0082
97	5.86	.0070	97	8.25	.0082
199	5.90	.0071	202	8.36	.0083
314	5.97	.0072	292	8.47	.0084
421	6.02	.0073	416	8.63	.0089
506	6.03	.0077	501	8.76	.0096
607	6.17	.0081	605	8.98	.0123
32	5.82	.0069	27	8.19	.0080

Silicate glasses (cont.)

X994

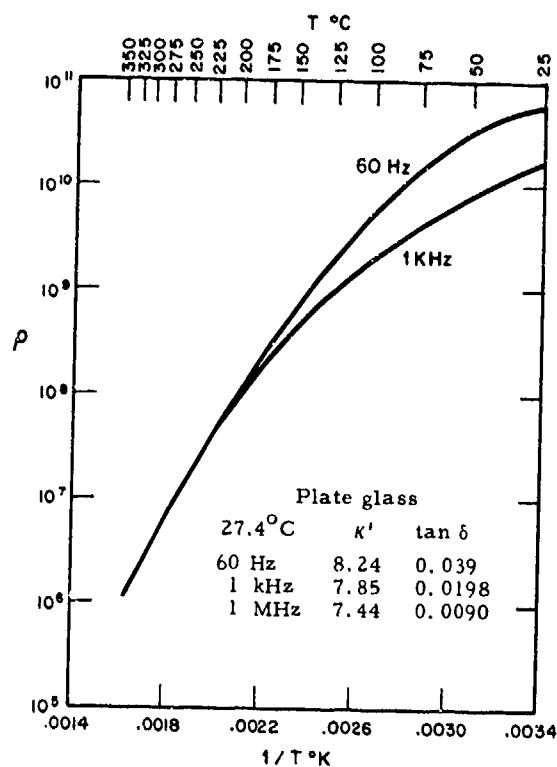
Owens Corning



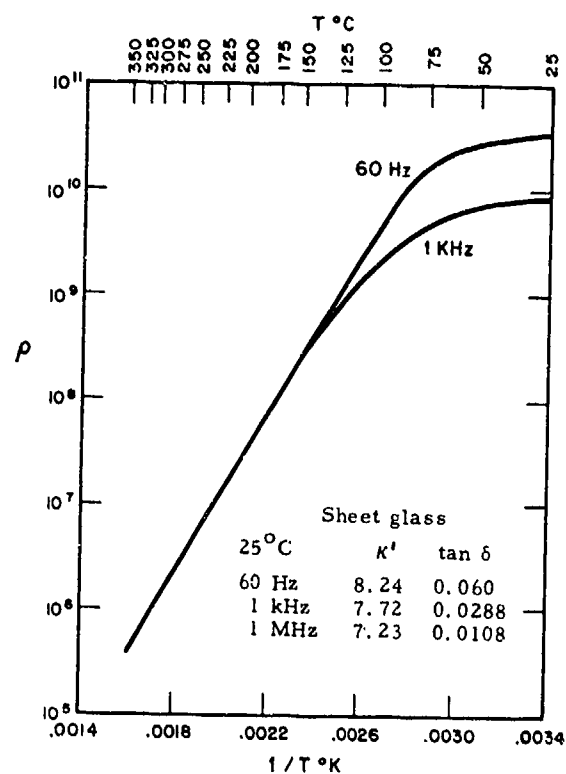
# Glasses (cont.)

Pittsburgh Plate Glass Co.

Plate glass



Sheet glass



## Silicon dioxide, sintered

Slip-cast

Density 1.957 g/cm<sup>3</sup>

Brunswick

Freq., Hz	25°C		100°C		200°C		300°C		400°C		500°C	
	$\kappa$	$10^4 \tan \delta$	$\kappa$	$10^4 \tan \delta$	$\kappa$	$\tan \delta$	$\kappa$	$\tan \delta$	$\kappa$	$\tan \delta$	$\kappa$	$\tan \delta$
10 <sup>2</sup>	3.38	7.1	3.39	11.0	3.44	.0190	4.42	.896	7.91	9.51	19.1	33.8
3x10 <sup>2</sup>	3.38	8.6										
10 <sup>3</sup>	3.38	8.8	3.38	7.8	3.41	.99364	3.64	.178	5.09	1.66	7.57	9.00
2x10 <sup>3</sup>	3.38	7.3										
5x10 <sup>3</sup>			3.38	7.7								
10 <sup>4</sup>	3.37	6.2	3.38	7.6	3.41	.00158	3.47	.0246	3.90	.334	5.10	1.47
5x10 <sup>4</sup>			3.38	8.3					3.5			
10 <sup>5</sup>	3.37	4.5	3.37	8.3	3.41	.00099	3.46	.00465	3.54	.055	3.90	.290
2x10 <sup>5</sup>			3.37	7.5								
10 <sup>6</sup>	3.37	3.7	3.37	6.1	3.40	.00081	3.45	.00158	3.49	.0089	3.61	.0483
6x10 <sup>6</sup>			3.37	3.6								
10 <sup>7</sup>	3.37	2.5	3.37	3.2	3.40	.00068	3.45	.0008	3.49	.0021	3.55	.0112
8.5x10 <sup>9</sup>	3.364	6.6										

## Silicon dioxide, with 2.5% chromium oxide

Slip-cast,

Density 1.928 g/cm<sup>3</sup>

Brunswick

Freq., Hz	25°C		100°C		200°C		300°C		400°C		500°C	
	$\kappa$	$\tan \delta$	$\kappa$	$\tan \delta$	$\kappa$	$\tan \delta$	$\kappa$	$\tan \delta$	$\kappa$	$\tan \delta$	$\kappa$	$\tan \delta$
10 <sup>2</sup>	3.33	.00345	3.43	.0057	3.57	.0292	4.59	.935	8.73	9.39	36.7	42.4
10 <sup>3</sup>	3.33	.00257	3.42	.0043	3.51	.0113	3.72	.179	5.17	1.76	13.5	10.1
10 <sup>4</sup>	3.32	.00174	3.36	.0034	3.48	.0071	3.59	.0292	3.95	.324	6.09	2.41
10 <sup>5</sup>	3.32	.00152	3.34	.0027	3.40	.0054	3.51	.0109	3.63	.0537	4.39	.425
10 <sup>6</sup>	3.31	.00093	3.33	.0020	3.38	.0040	3.49	.0101	3.56	.0149	3.82	.094
10 <sup>7</sup>	3.31	.00035	3.32	.0017	3.34	.0022	3.42	.0076	3.53	.0106	3.68	.032
8.5x10 <sup>9</sup>	3.29	.00112										

Silicon dioxide, sintered

Code 7941

Density 1.923 g/cm<sup>3</sup>

Corning Glass

Freq., ~8.5 GHz

Corning Multiform Glass

T <sup>o</sup> C	$\kappa$	$\tan \delta$
25	3.323	.0005
279	3.351	.0009
517	3.378	.0014
769	3.408	.0023
910	3.431	.0028
1043	3.451	.0037
1205	3.455	.0051
1372	3.513	.0091

At 8.52 GHz, 25<sup>o</sup>C, density = 1.906 g/cm<sup>3</sup>  
 $\kappa = 3.27$ ;  $\tan \delta = .00063$

Silica, slip-cast

Dynasil Corp. of America

8.6 GHz, 25<sup>o</sup>C

<u>Sample</u>	Density (g/cm <sup>3</sup> )	$\kappa$	$\tan \delta$
DSCX-3	1.970	3.395	.00058
DSCX-8E	2.038	3.513	.00054

Quartz fiber

Sample AS-3DX-1R

Source: Philco Ford Corp.  
Newport Beach, Calif. 92663

Manufacturer: Fiber Materials Inc.  
Graniteville, Mass. 01829

Freq., 8.52 GHz		
T°C	K	tan δ
25*	3.02	.0054
25	2.98	.0019
98	2.97	.0018
198	2.96	.0016
307	2.95	.0015
418	2.95	.0014
497	2.945	.0014
591	2.95	.0016
729	2.96	.0022
828	2.975	.0029
905	2.99	.0035
995	3.01	.0042

\* As received, other values after vacuum bake  
for 24 hours at 125°C.

Silica fiber composites

Philco-Ford Corp., Aeronutronic Div.

Sample 1-VH-O-M-1, 25°C		(Hz) 10 <sup>5</sup>	10 <sup>6</sup>	10 <sup>7</sup>	7.5x10 <sup>7</sup>	1.8x10 <sup>8</sup>
As received,	K	2.779	2.777	2.777	2.775	2.772*
density 1.536 g/cm <sup>3</sup>	10 <sup>4</sup> tan δ	4.6	8.3	6.4	13.4	17*
After 18 hrs.	K			2.77	2.77	2.77*
vacuum oven 80°C	10 <sup>4</sup> tan δ			4.6	9.1	11.5*

\* Extrapolated values.



## Silica fiber composites (cont.)

Philco-Ford Corp., Aeronutronic Div.

Sample 1-XB-O-M

Density 1.653 g/cm<sup>3</sup>

8.52 GHz

	T <sup>o</sup> C	K	tan δ
As received, Face 1 up	25	2.919	.0062
Face 2 up	25	2.956	.0064
After vacuum oven			
80 <sup>o</sup> C, 10 days			
Face 2 up	25	2.938	.00162
Face 1 up	25	2.895	.00169
	115	2.89	.0012
	246	2.89	.0006
	357	2.90	.0005
	438	↓	.0006
	535		.0008
	608		.0010
	710		.0014
	805		.0020
	908		.0026
	972		.0028
	1000	↓ *	.0031*
* Extrapolated values.	25	2.89	.00042

Sample AS-3DX 176-17 at 8.5 GHz, density = 1.626 g/cm<sup>3</sup>

T <sup>o</sup> C	K	tan δ
25	2.873 ± .005	.00355
94	2.86 ± .01	.00199
203	2.86	.00054
288	2.85	.00040
377	2.85	.00043
466	2.85	.00054
535	2.86 ± .02	.00068
289	2.85	.00042
27	2.840 ± .005	.00038 ± .00003

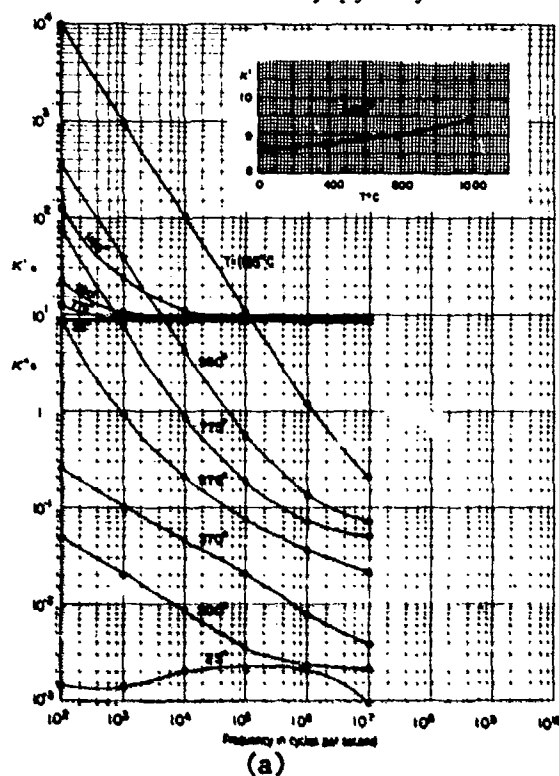
Silica fibers in aluminum phosphate matrix  
ChemCeram

Whittaker Corp.

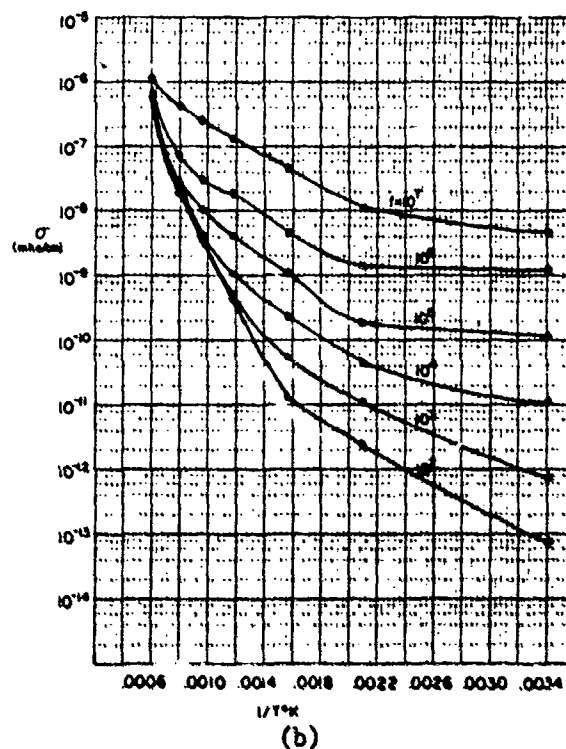
<u>Sample</u>	T°C	8.52 GHz		Density (g/cm <sup>3</sup> )
		K	tan δ	
1, as received	5	2.73	.0051	1.547
2, as "	25	2.70	.0060	1.543
2, dried*	25	2.68	.0043	(wt. loss .049%)
2, room humidity	25	2.70	.0050	
	116	2.70	.0050	
	235	2.71	.0053	
	410	2.71	.0080	
	495	2.71	.0105	
	580	2.72	.0140	
	673	2.72	.0177	
	760	2.72	.0228	
	827	2.73	.0265	
	916	2.74	.0315	
	967	2.75	.038	
	25	2.71	.0047	

\* 4 days at 120°C in vacuum oven.

# Silicon nitride, pyrolytic



# North American Aviation



## Silicon nitride ceramic

At 8.52 GHz, density 2.449 g/cm<sup>3</sup>

T°C

25

170

323

446

586

674

714

864

912

991

509

348

K

5.54

5.54

5.54

5.55

5.55

5.56

5.57

5.58

5.59

5.63

5.55

5.54

tan delta

.0036

.00375

.0040

.00365

.0030

.0050

.0054

.00615

.00630

.00665

.0034

.0040

## Admiralty Materials Laboratory

## Silicon nitride ceramic,

after vacuum drying at 100°C, at 8.5 GHz

Density 2.128 g/cm<sup>3</sup>

## Raytheon Company

T°C

25

K

5.15

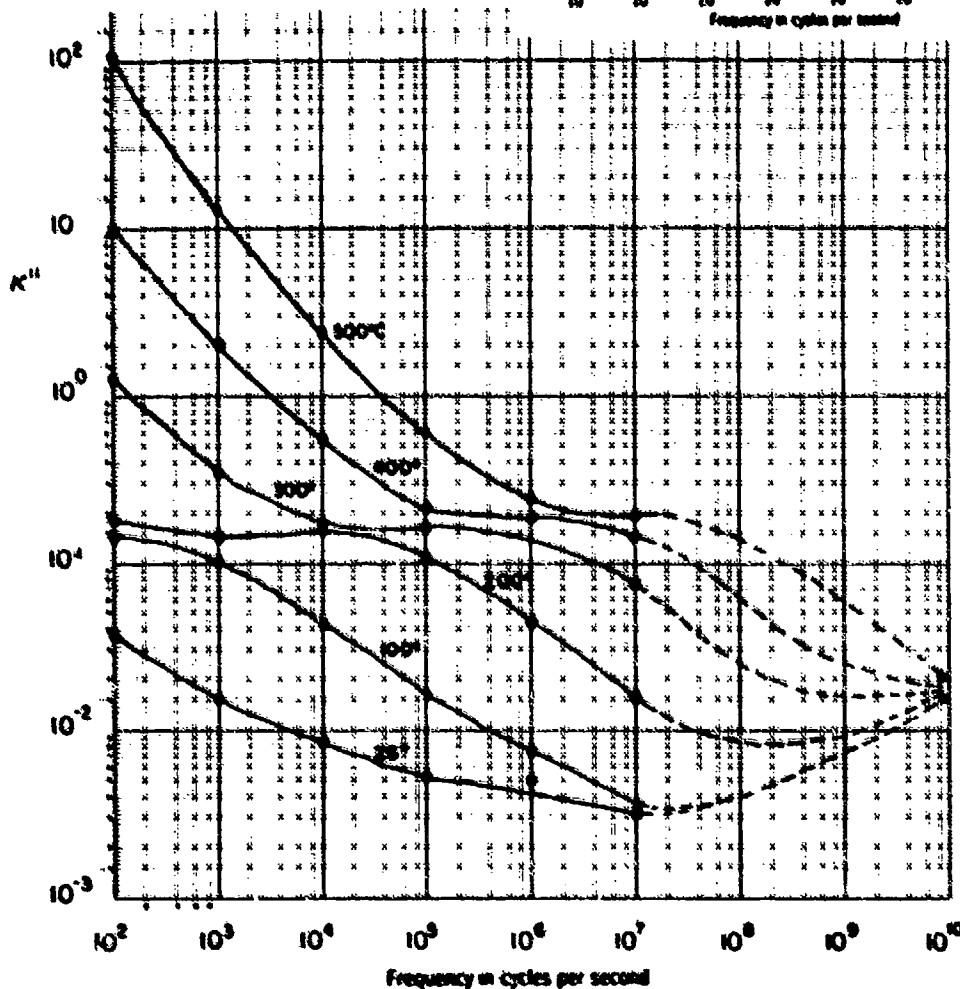
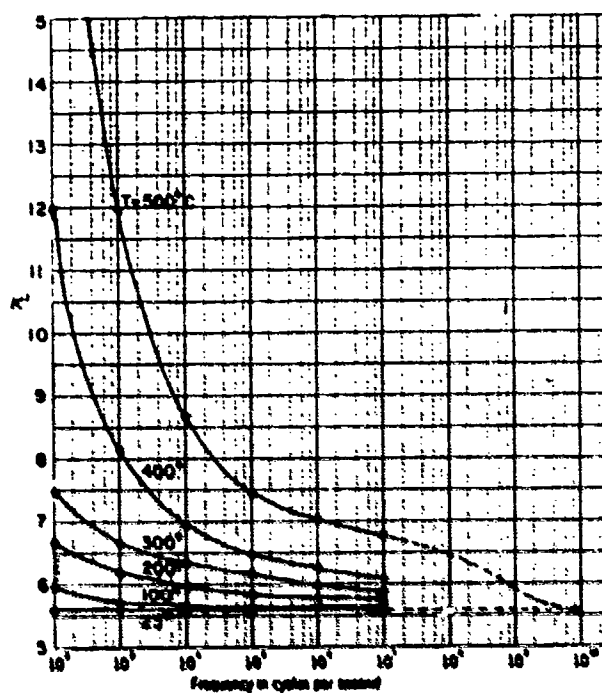
tan delta

0.00037

Silicon nitride ceramic,  
technical grade,  
density 2.456 g/cm<sup>3</sup>,  
measured in dry nitrogen

Haynes Stellite  
Division of Union Carbide

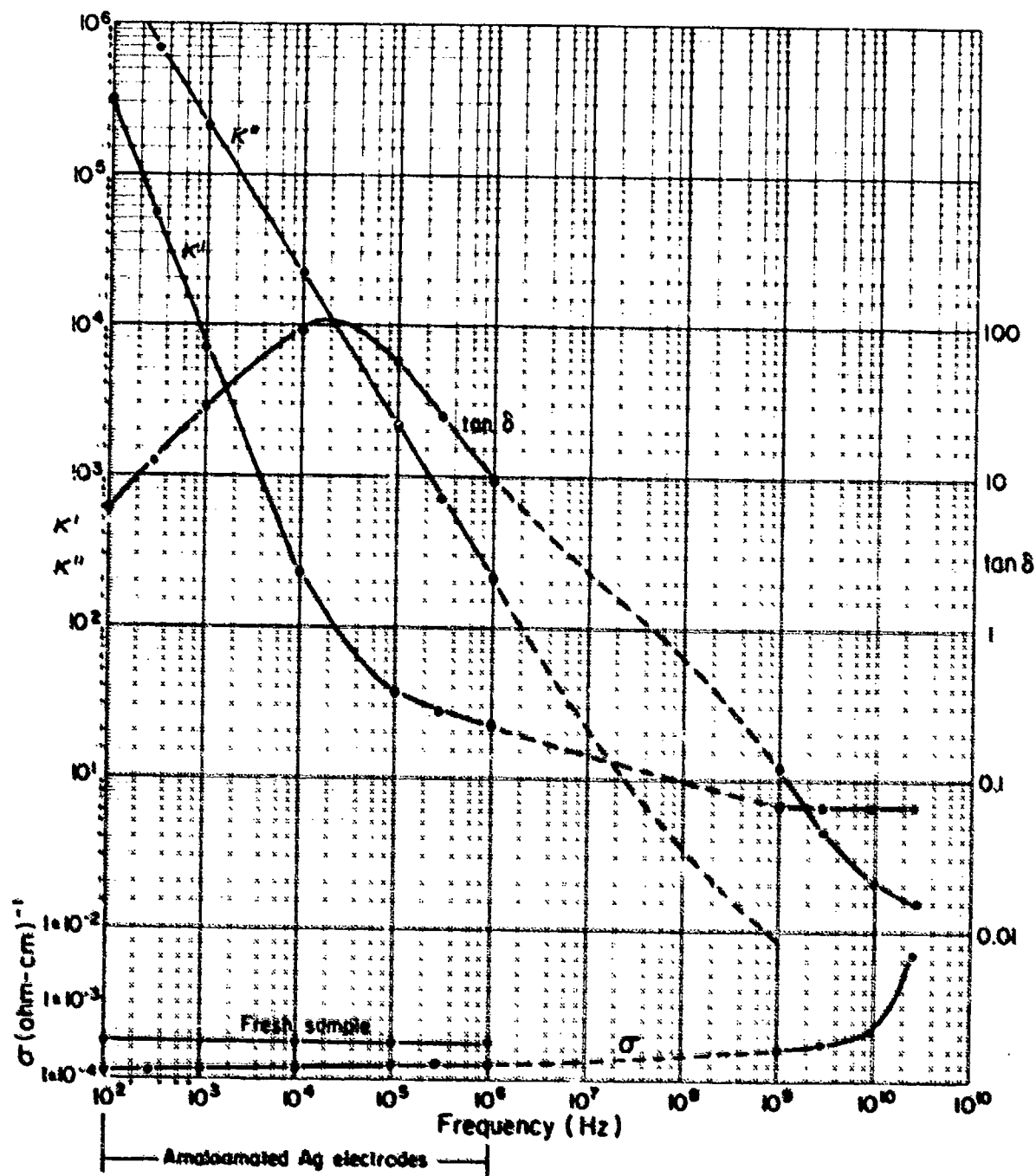
(a)  
Dielectric constant  
vs. frequency



(b)  
Dielectric loss  
factor versus  
frequency

Silver iodide, pressed powder  
at 10,000 psi, 27°C,  
aged several weeks  
unless noted

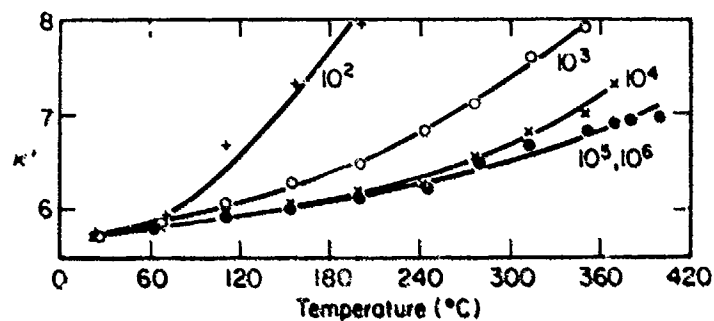
Massachusetts Institute of Technology  
Laboratory for Insulation Research



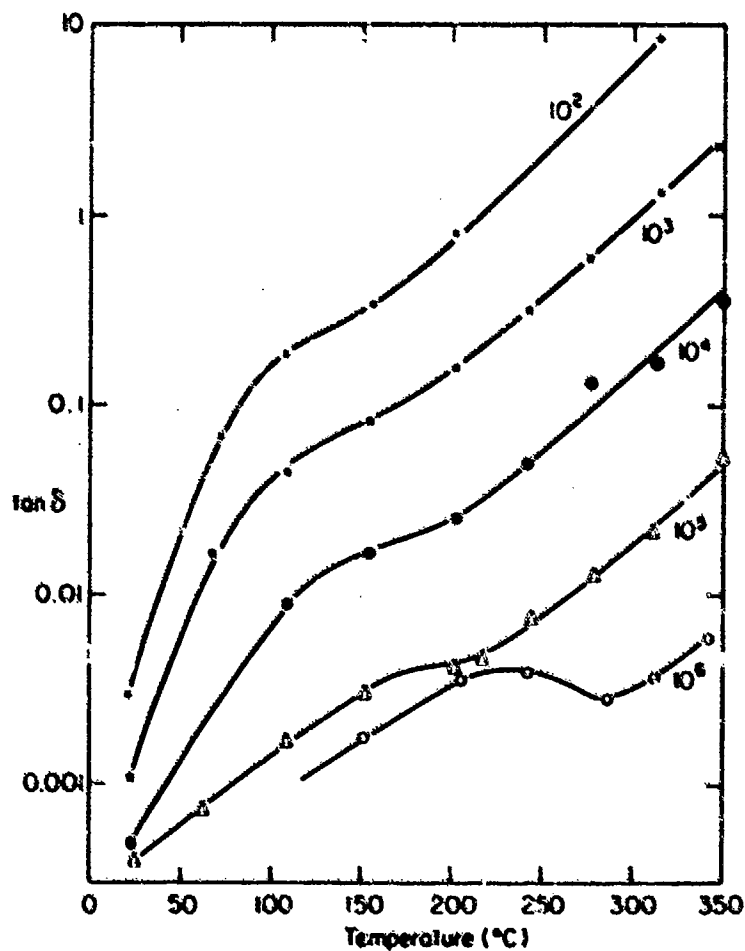
Sodium chloride, doped  
(0.075 mole %  $\text{BiCl}_3$ )

M.I.T., Crystal Physics Laboratory

Variation of dielectric constant with  
temperature at different frequencies

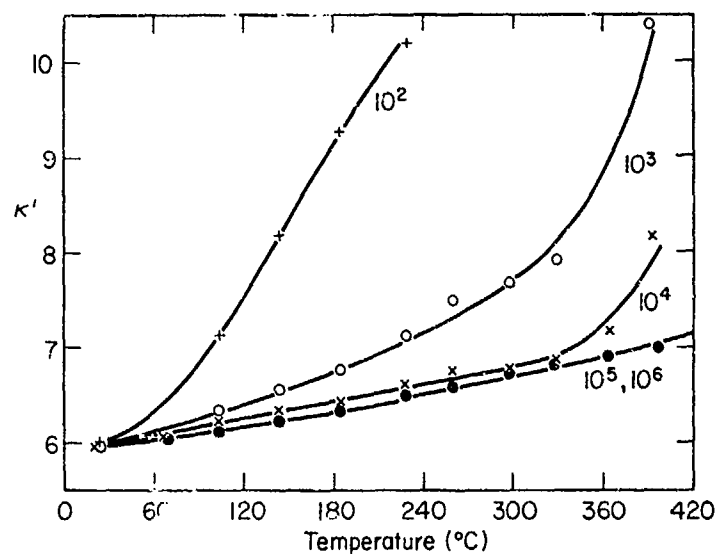


Dielectric loss as a function of  
temperature at different frequencies

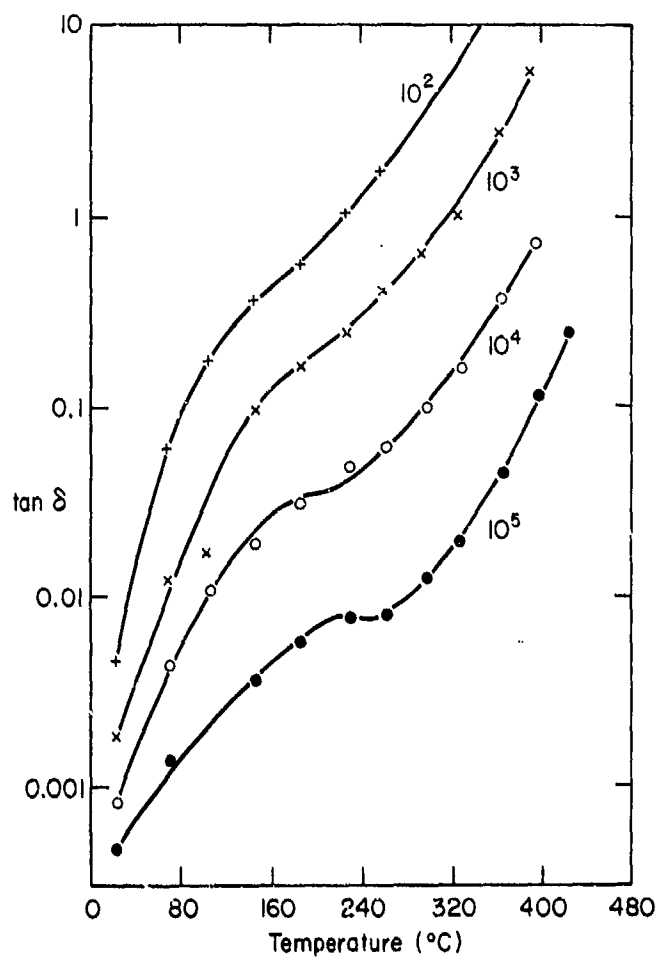


Sodium chloride, doped (cont.)  
(1.23 mole %  $\text{BiCl}_3$ )

Variation of dielectric constant with  
temperature at different frequencies



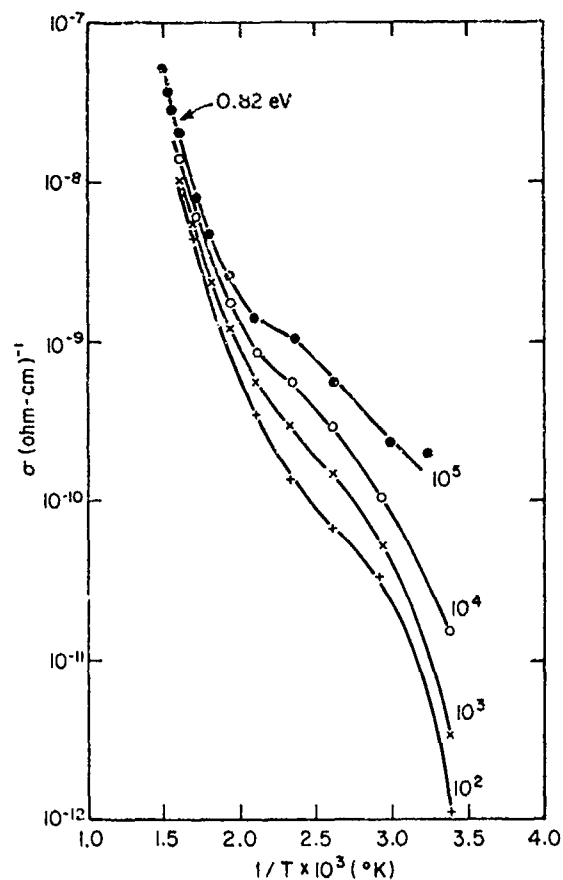
Dielectric loss as a function of  
temperature at different frequencies



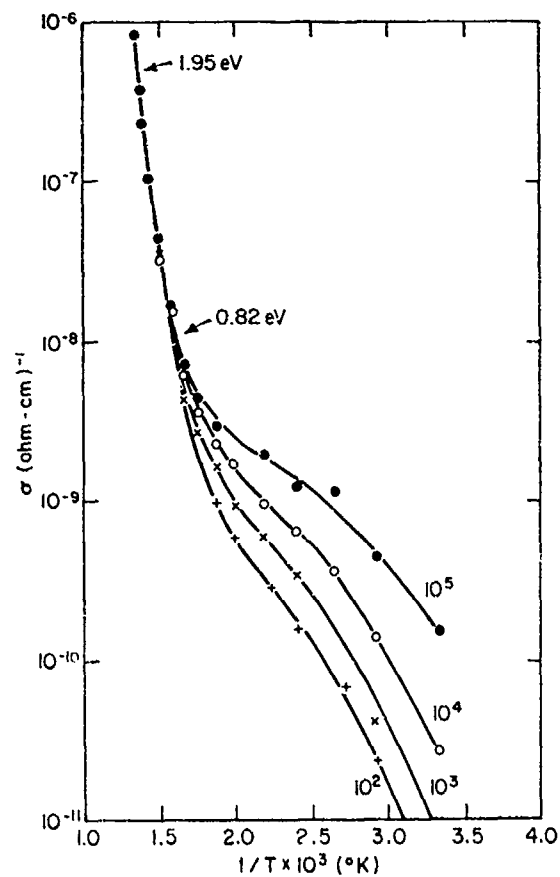
Sodium chloride (cont.)

Specific conductivity as a function of  $1/T$   
at different frequencies

(0.075 mole %  $\text{BiCl}_3$ )



(1.23 mole %  $\text{BiCl}_3$ )

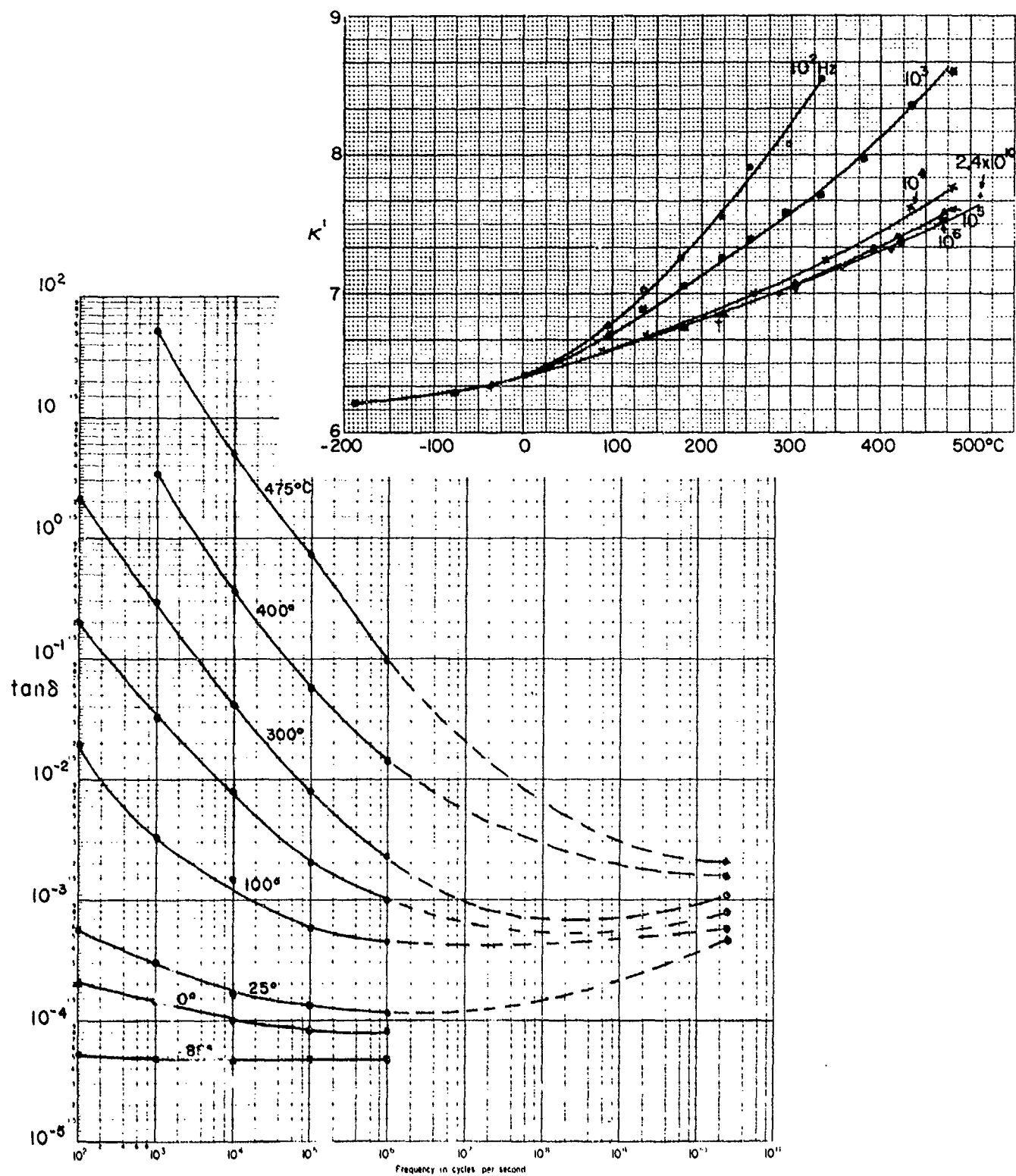




# Strontium fluoride

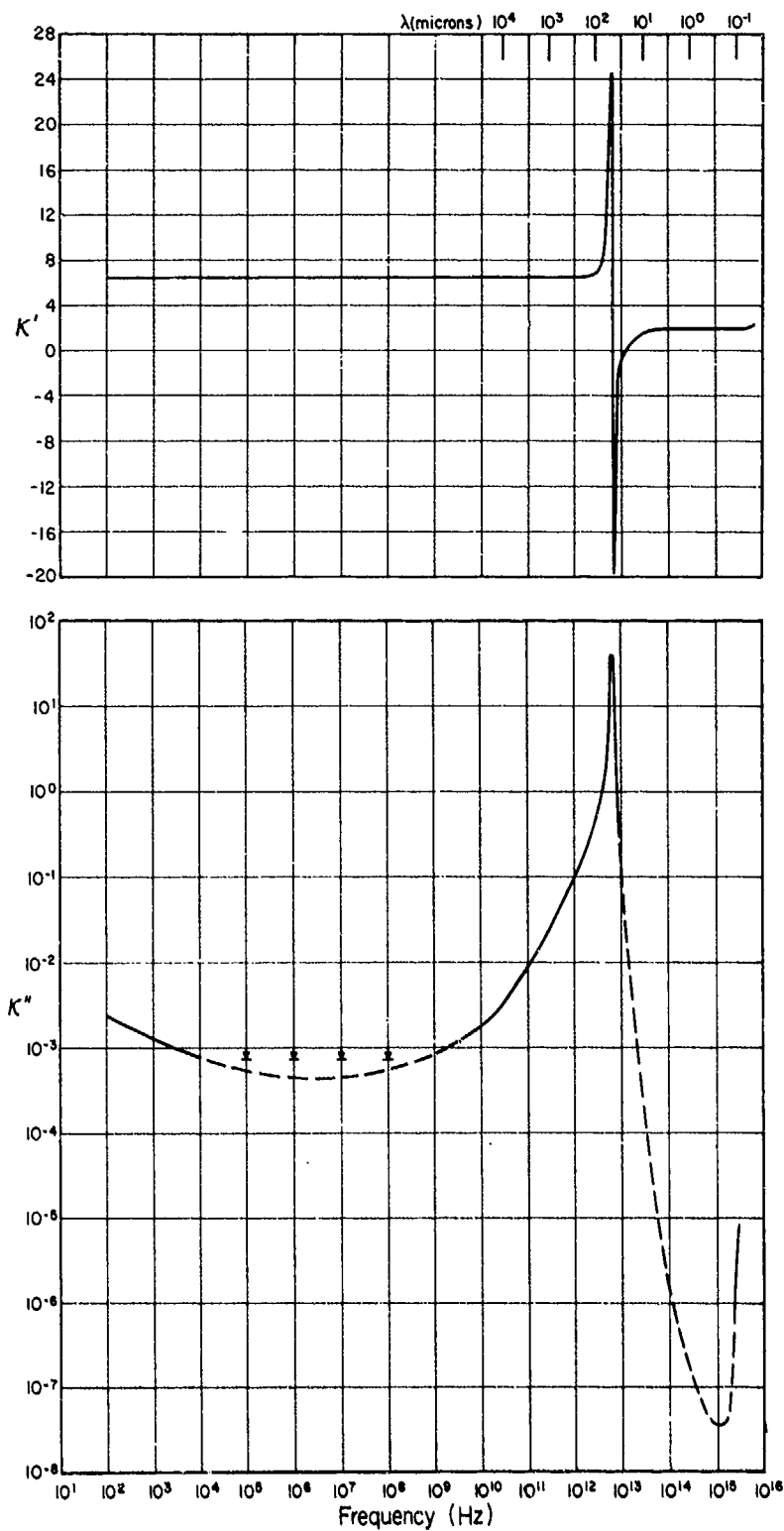
M. I. T., Crystal Physics Lab.

For more complete data see  
K. V. Rao and A. Smakula,  
J. Appl. Phys. 37, 319 (1966).



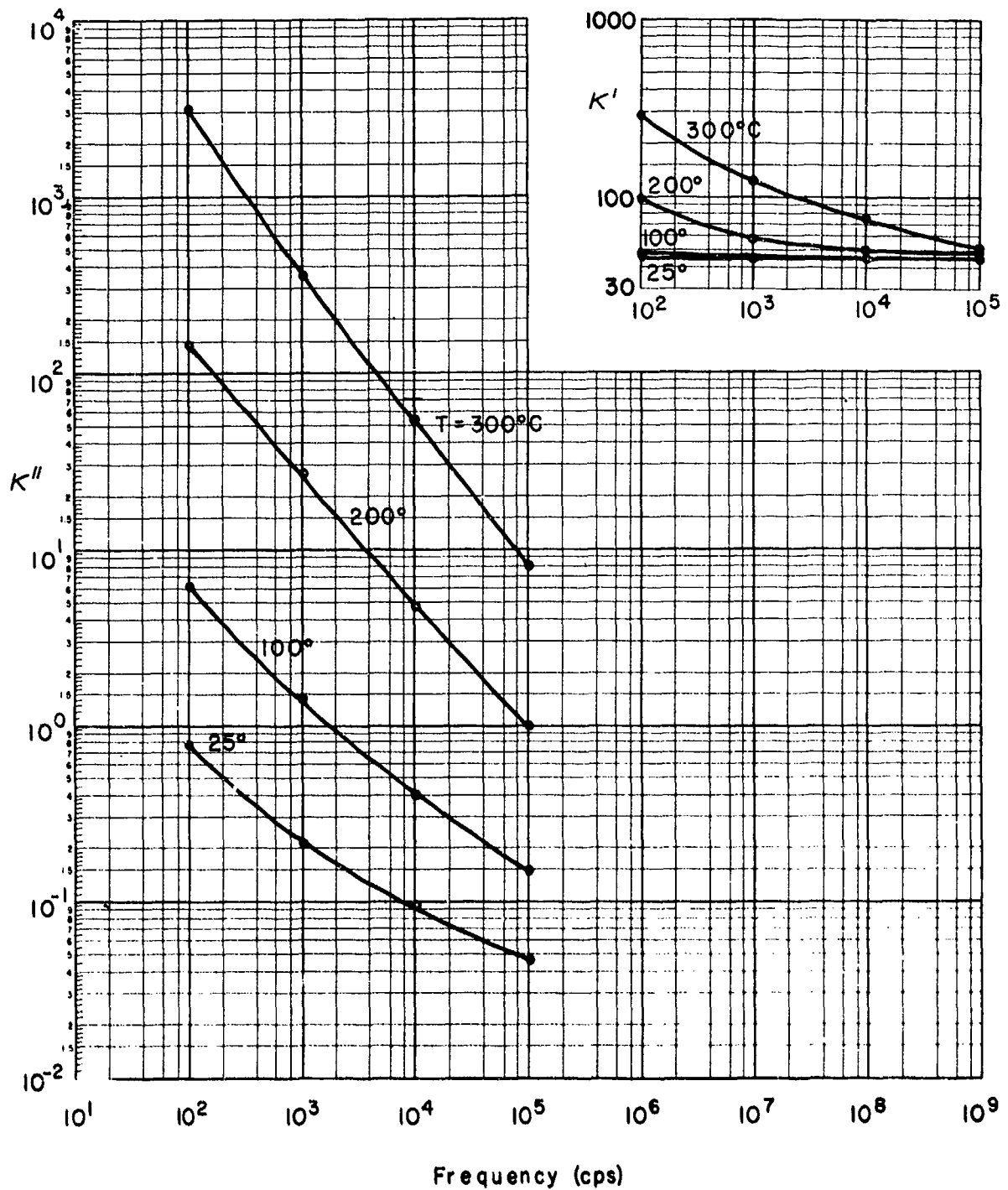
Strontium fluoride (cont.)  
Single crystal

M.I.T., Crystal Physics Lab.



Ta<sub>2</sub>O<sub>5</sub> ceramic, hot-pressed from  
Ciba optical grade powder,  
density 8.27 g/cm<sup>3</sup>

Massachusetts Institute of Technology  
Laboratory for Insulation Research



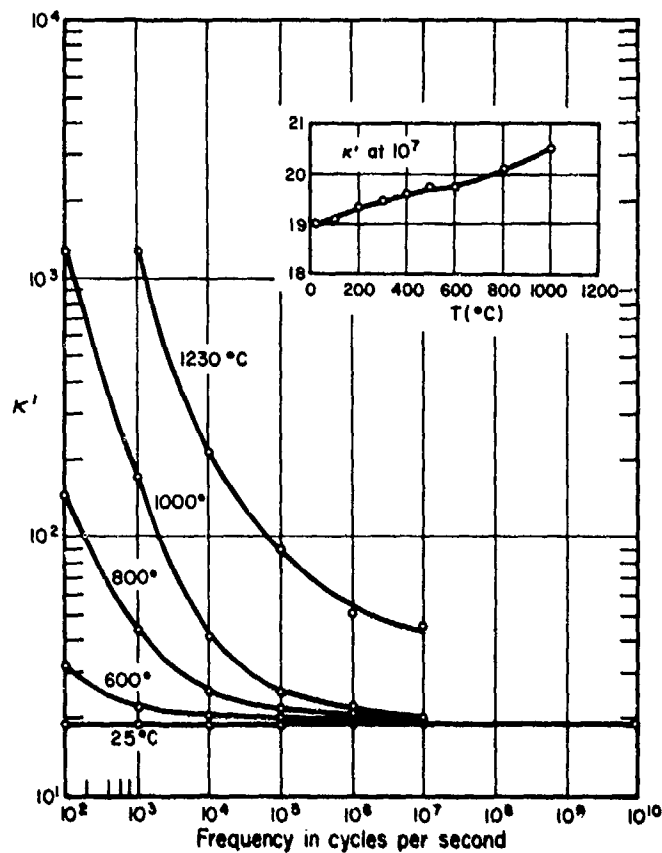
## Thallium halides

M. I. T., Crystal Physics Lab.

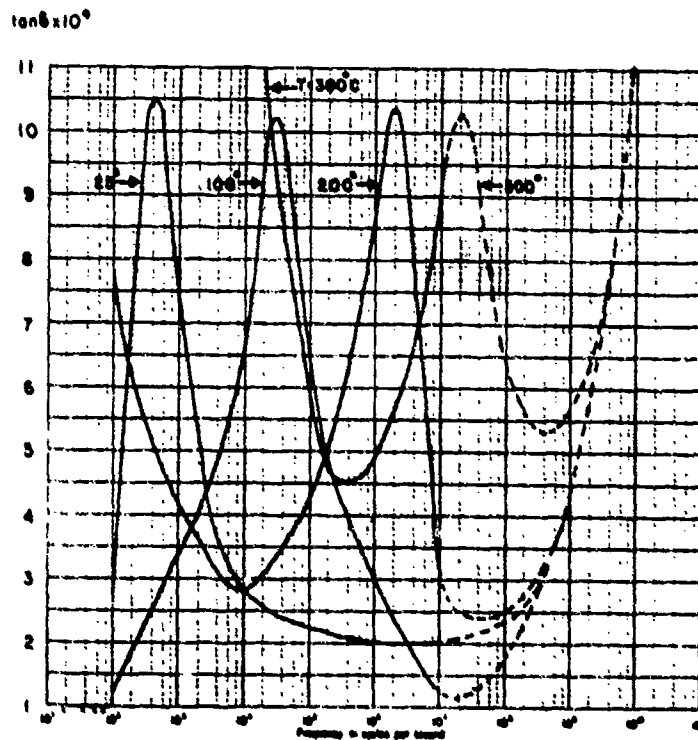
Material	$\kappa'$ , 25°C 10 <sup>6</sup> Hz	$\kappa'$ , 4°K	$\tan \delta$ , 25°C 10 <sup>6</sup> Hz	Activation energy for conduction in eV
TlF pressed	19.7	-	.00015	-
TlCl	31.9	-	.00006	.73
TlBr	30.4	-	.00005	.77
TlI polycrystalline	20.4	20.0	.00024	-
KRS6 (TlCl) <sub>.7</sub> -(TlBr) <sub>.3</sub>	32.2	38.4	.000075	.71
KRS5 (TlBr) <sub>.42</sub> -(TlI) <sub>.58</sub>	32.4	-	.00016	.66
TlI + CsI .01	32.5	39.4	.000068	.65

For more complete data see reports under Contract AF 19(628)-395.

Thorium oxide ceramic, nuclear grade Zircoa, measured in air except at room temperature in dry nitrogen. Densities: of disk 9.852 g/cm<sup>3</sup>; cylinder 9.774 g/cm<sup>3</sup>



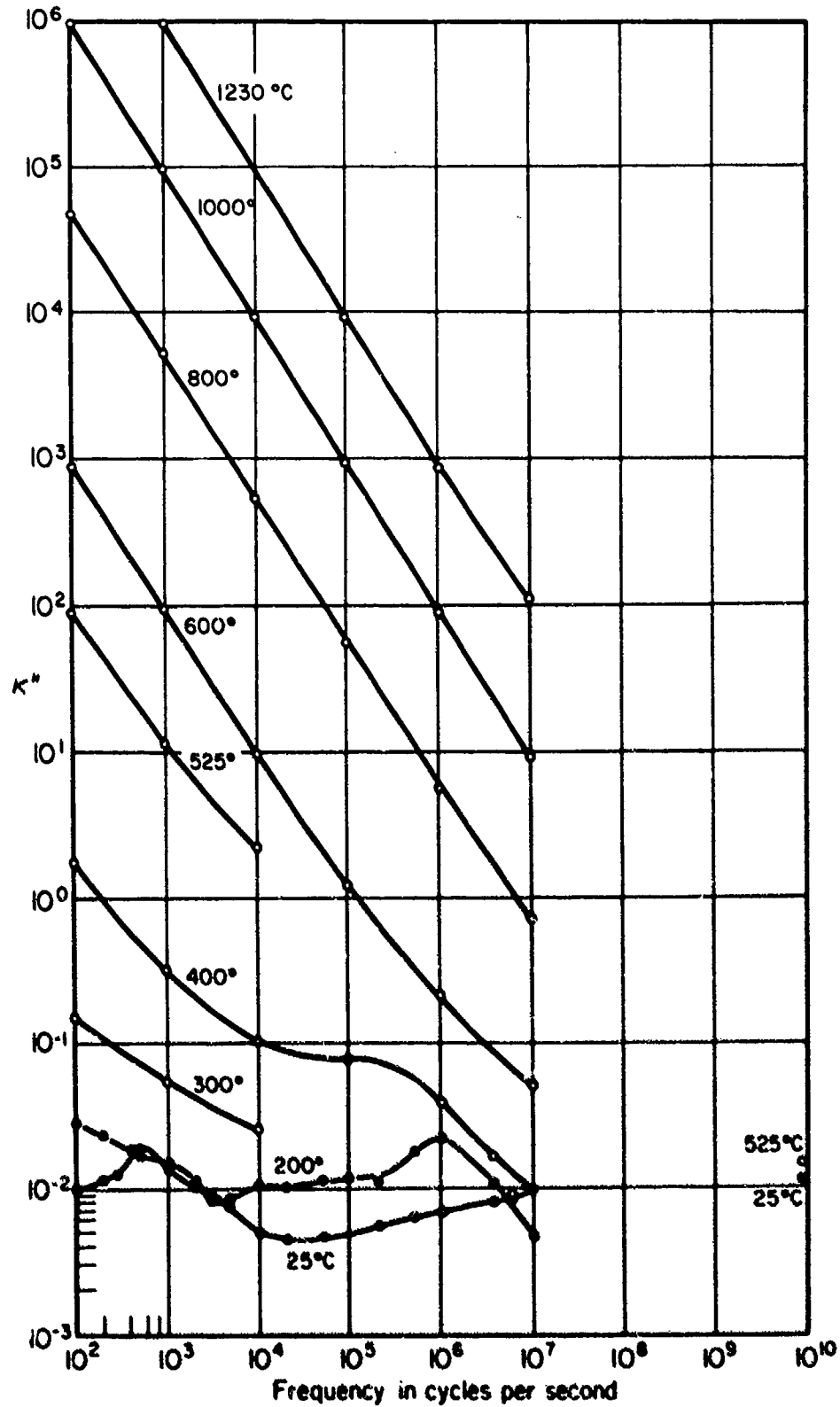
Dielectric constant  $\kappa''$  vs. frequency and temperature shows build-up of low-frequency polarization and small temperature coefficient at  $10^7$  Hz.



Dielectric loss tangent at low temperatures shows peak moving to high frequencies with a low activation energy (0.51 eV).

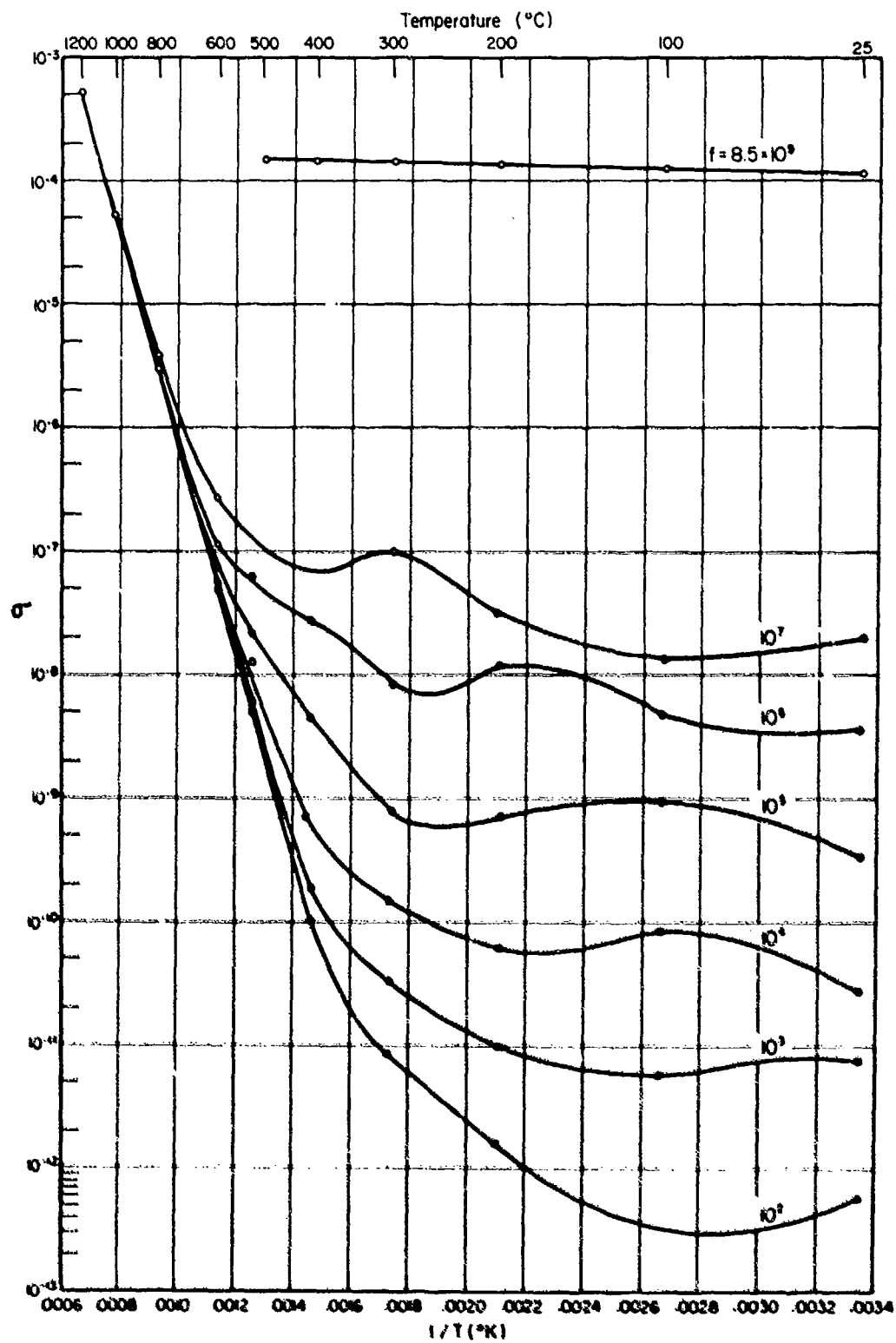
Thorium oxide ceramic (cont.)

Dielectric loss factor  $\kappa''$  versus frequency shows ease of conduction when many hot electrons are available

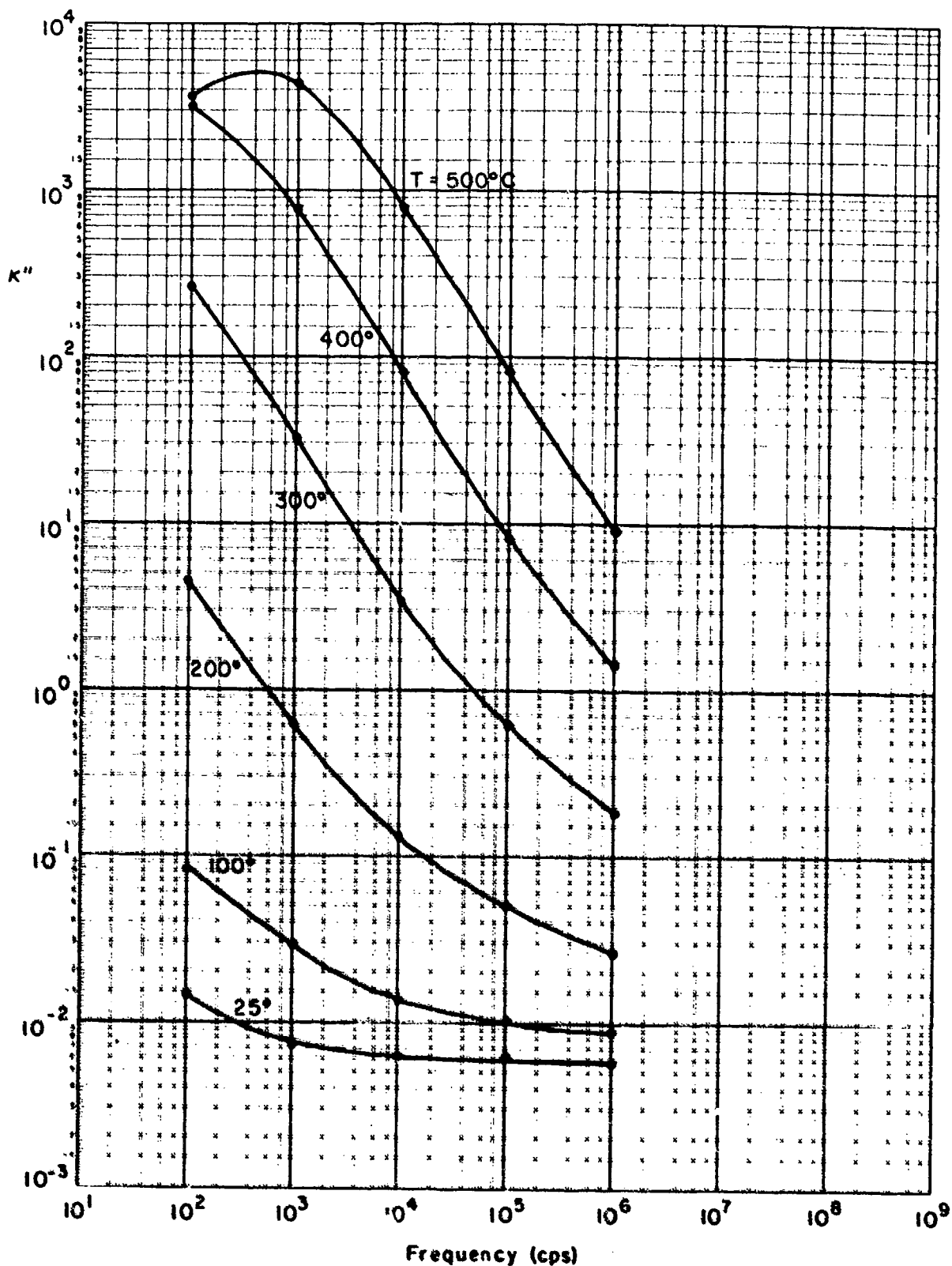


Thorium oxide ceramic (cont.)

Conductivity vs. reciprocal temperature shows intrinsic conduction range having activation energy of 1.70 eV.

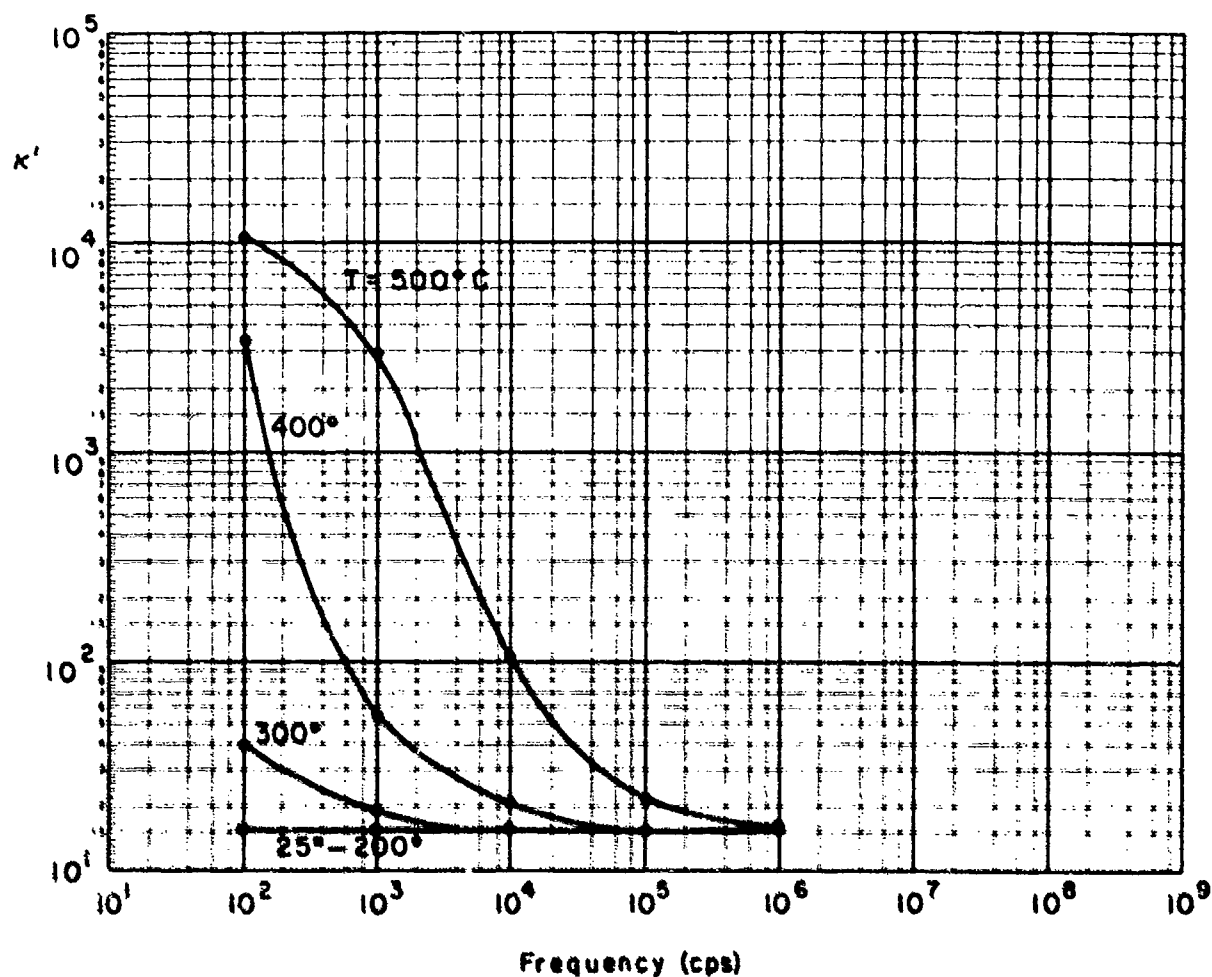


ThO<sub>2</sub> ceramic, Laboratory for Insulation Research; minor constituents  
Mg, Pb, Zn; traces of Ca, Cu, Fe, Si; density = 8.77 g/cm<sup>3</sup>





ThO<sub>2</sub> ceramic, Laboratory for Insulation Research; minor constituents Mg, Pb, Zn; traces of Ca, Cu, Fe, Si; density - 8.77 g/cc.



Vanadium oxide (V<sub>2</sub>O<sub>3</sub>)

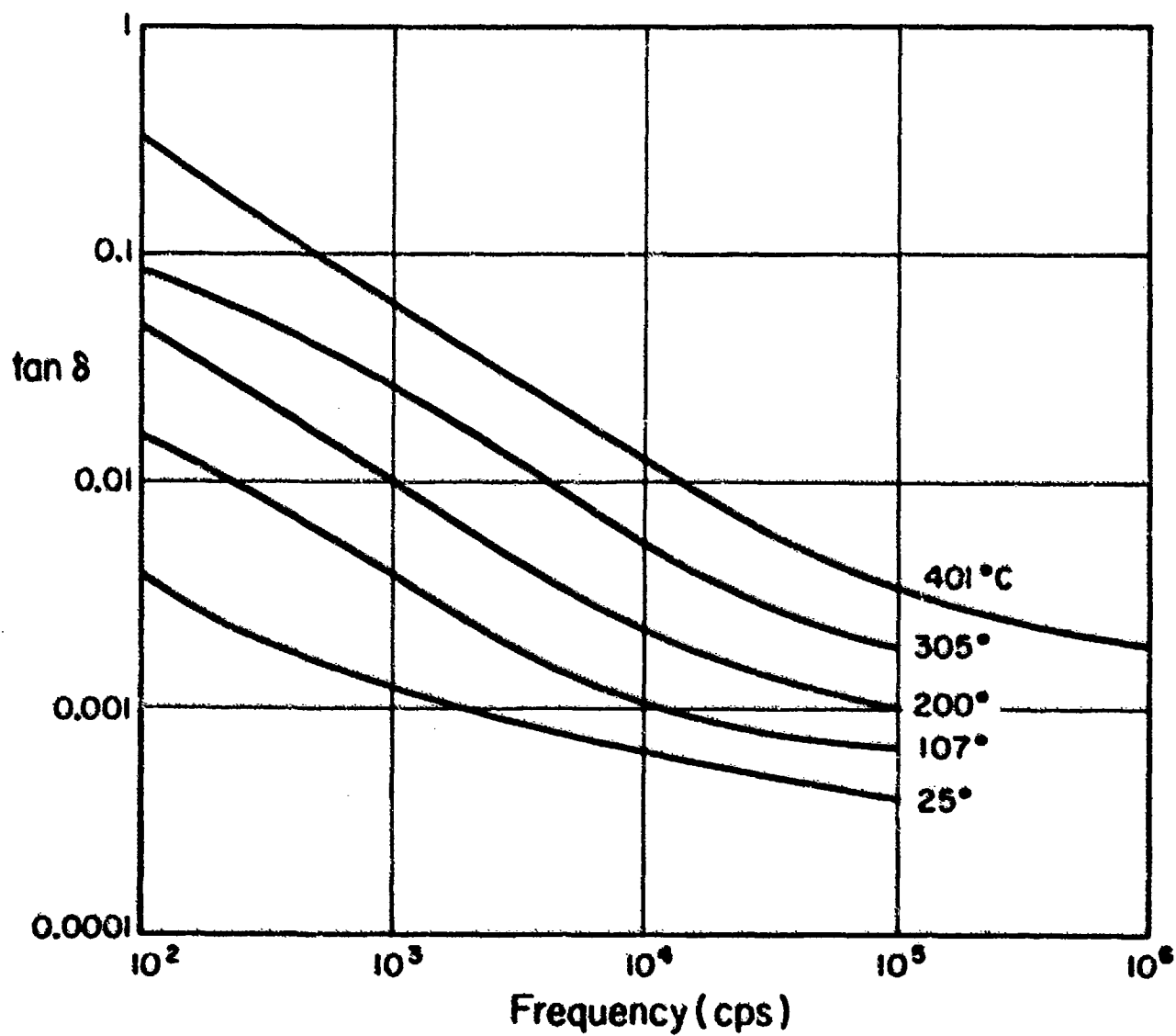
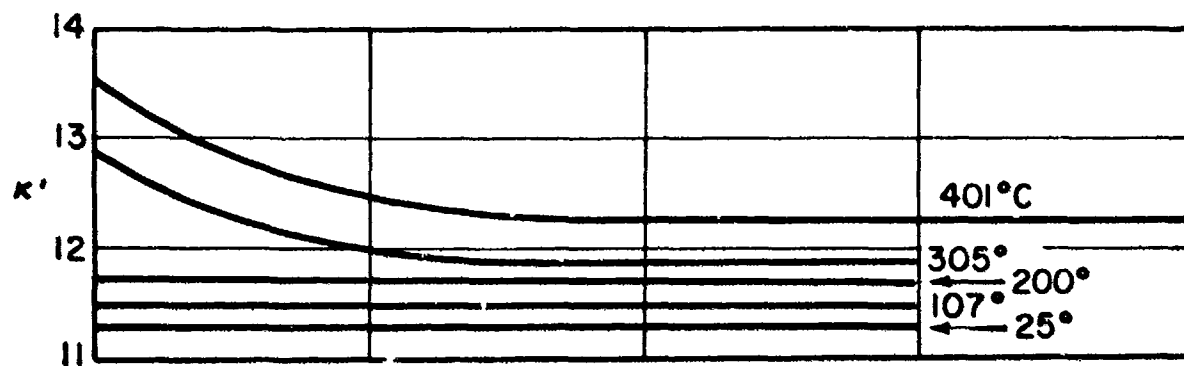
M. I. T., Lab. Ins. Research

Pressed powder samples, -185°C:

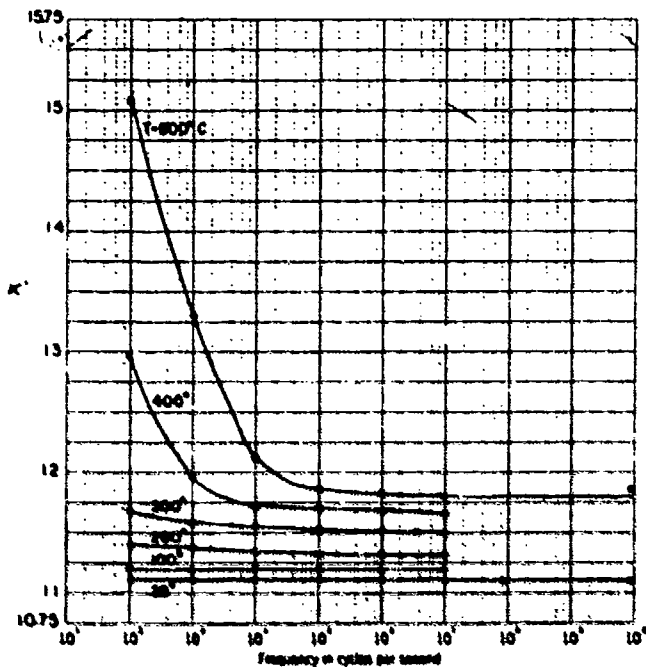
f (Hz)	κ' meas.	κ' corr. to full density	Density g/cm <sup>3</sup>
10 <sup>5</sup>	6.52	15.2	2.60
10 <sup>6</sup>	4.72	14.5	2.28

Yttrium oxide  
 $Y_2O_3$  crystal

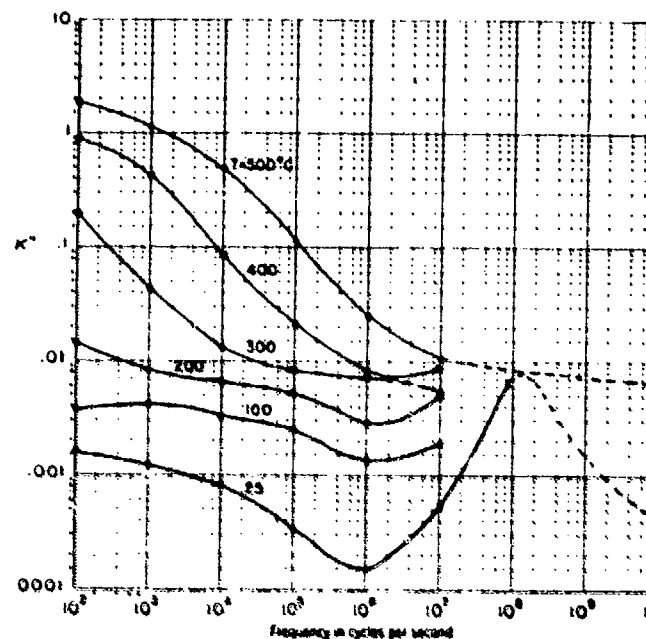
M.I.T., Laboratory for Insulation Res.



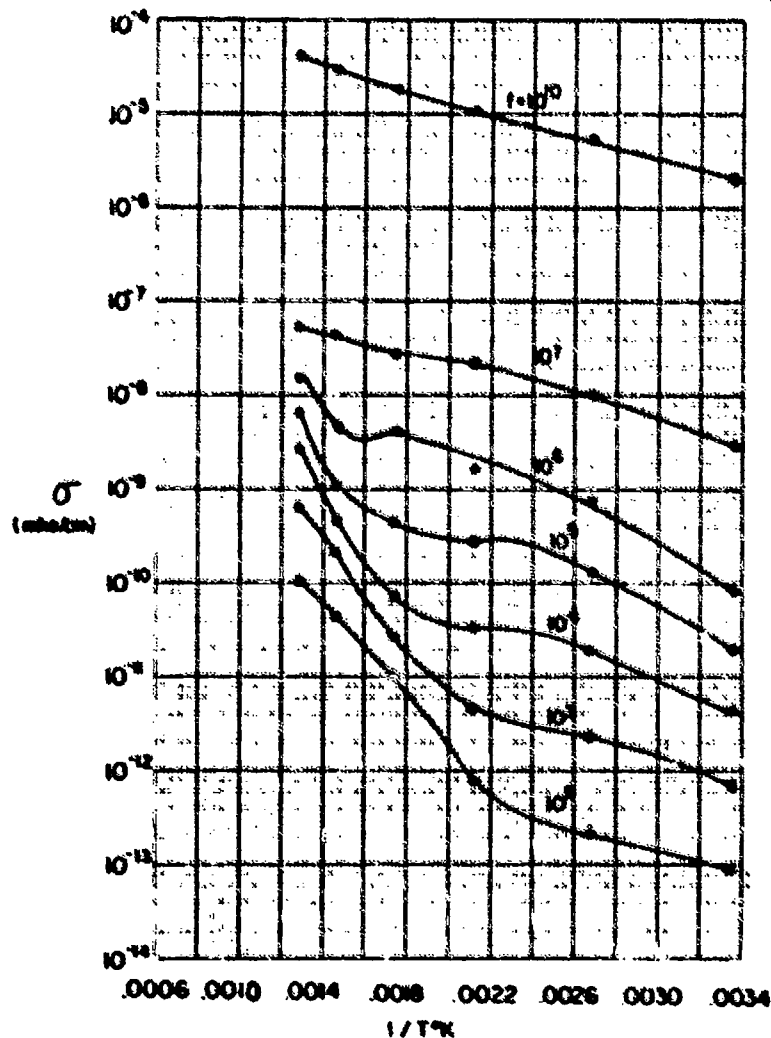
Yttrium oxide, nuclear grade (high purity 99.8%) ceramic, Zircoa;  
densities: of disk 5.1000, cylinder 4.917 g/cm<sup>3</sup>.



(a) Dielectric constant versus frequency



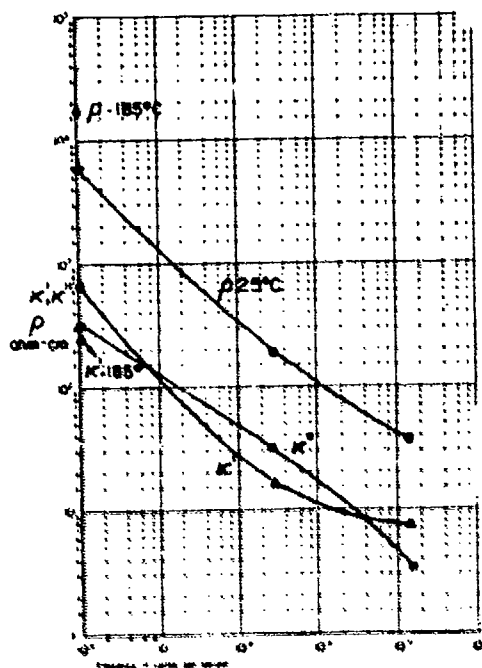
(b) Dielectric loss factor vs. frequency shows two dipole regions



(c) Conductivity versus  $1/T$  does not show intrinsic region

# Zinc oxide, single crystal

Airtron Div. of Litton Industries



Measurements of 1 and 300 MHz with electric field  $\parallel$  to c axis. At 14 GHz field was perpendicular.

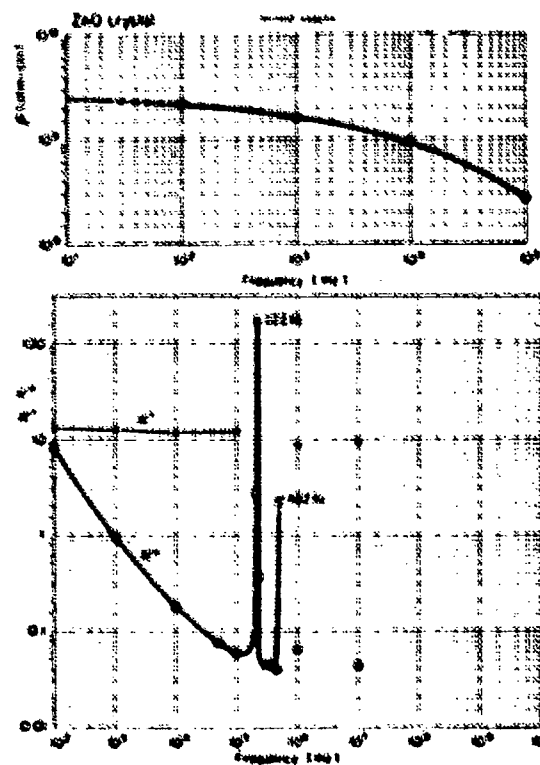
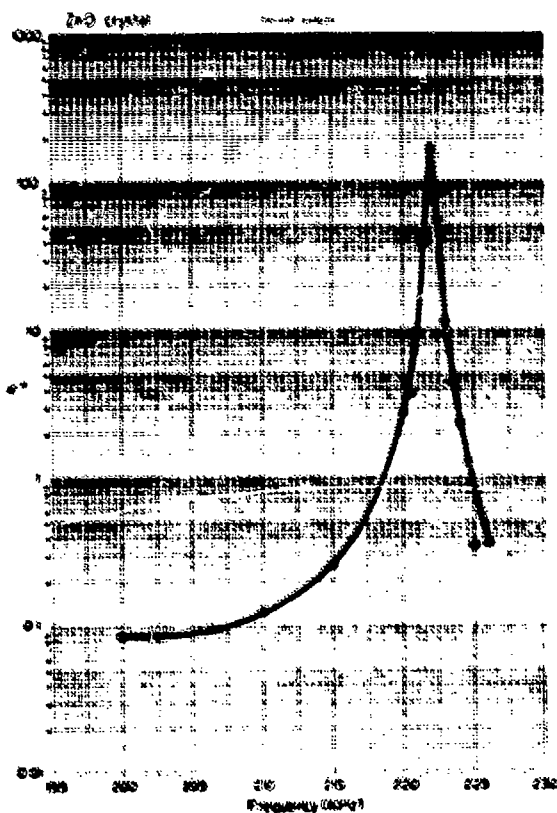
Second sample heat treated

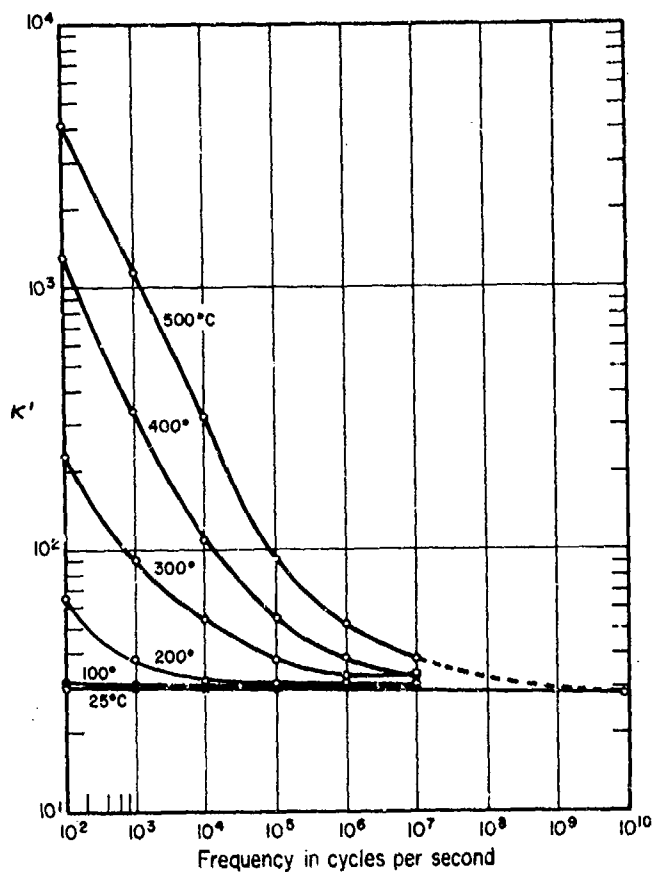
Major frequency resonances (kHz)

222  
482  
600  
677  
740

Dielectric constant

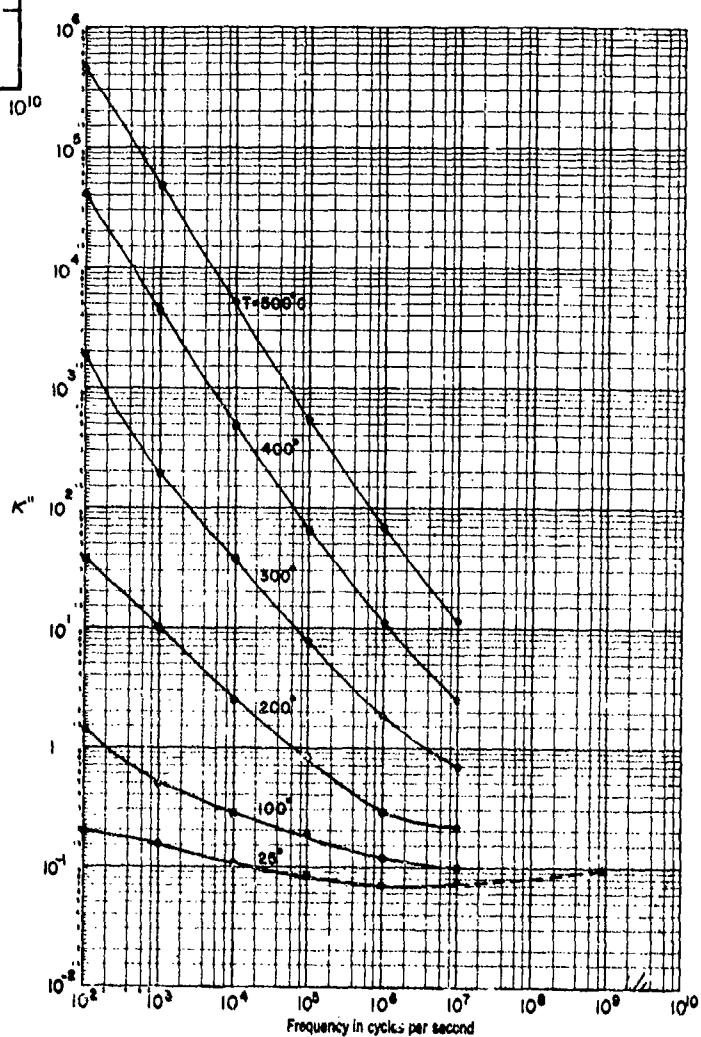
Hz	$\kappa$
$10^2$	12.29
$10^3$	12.07
$10^4$	11.90
$10^5$	12.13
$10^6$	8.35
$9.5 \times 10^6$	



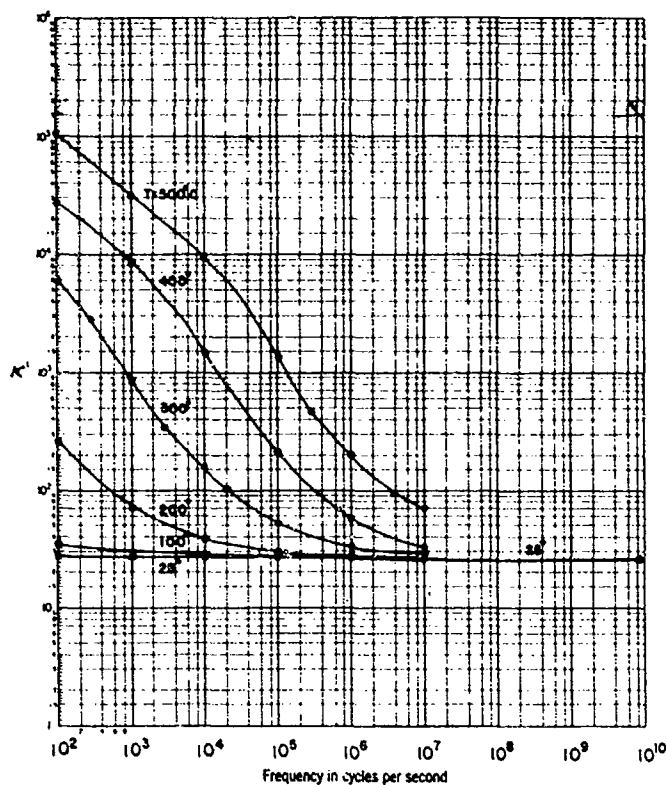


Zirconium oxide ( $ZrO_2$ ), mono-cubic, stabilized with lime ( $CaO$ ), technical grade ceramic Zircoa "C", densities of disk 5.696 g/cm<sup>3</sup>, of cylinder 5.646 g/cm<sup>3</sup>. Dielectric constant vs. frequency showing large grain-boundary polarization.

Dielectric loss factor versus frequency.



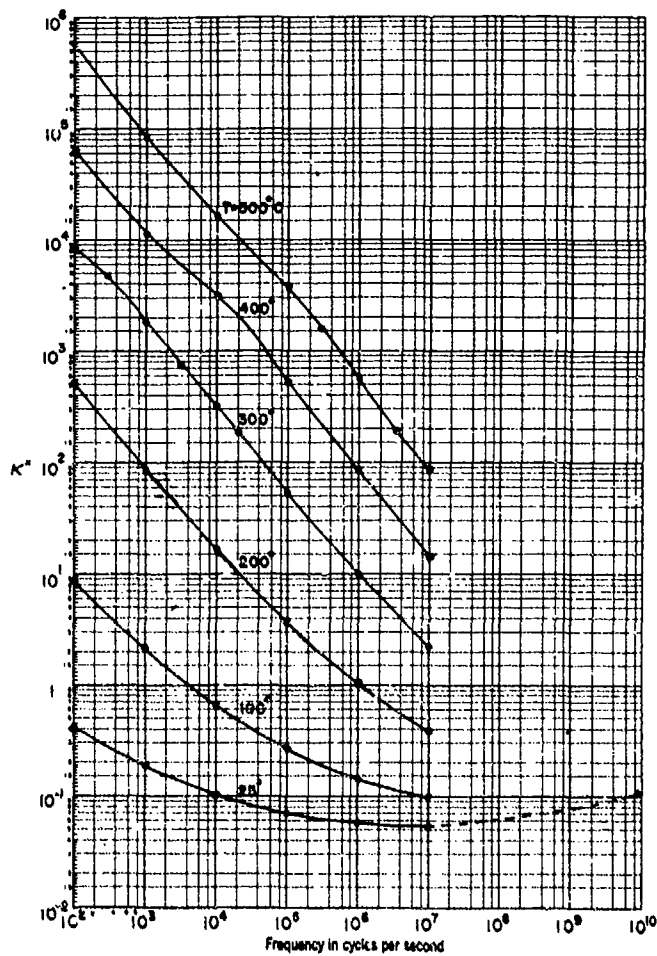
See also page 121

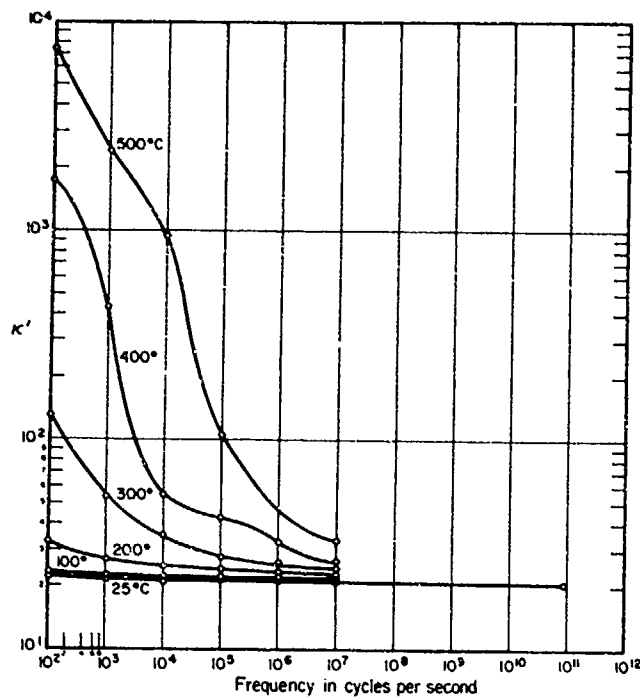


Zirconium oxide stabilized with 8%  $Y_2O_3$  nuclear grade ceramic Zircoa Y-904; densities of disk 5.444 g/cm<sup>3</sup>, of cylinder 5.647 g/cm<sup>3</sup>. Dielectric constant versus frequency

Dielectric loss factor versus frequency

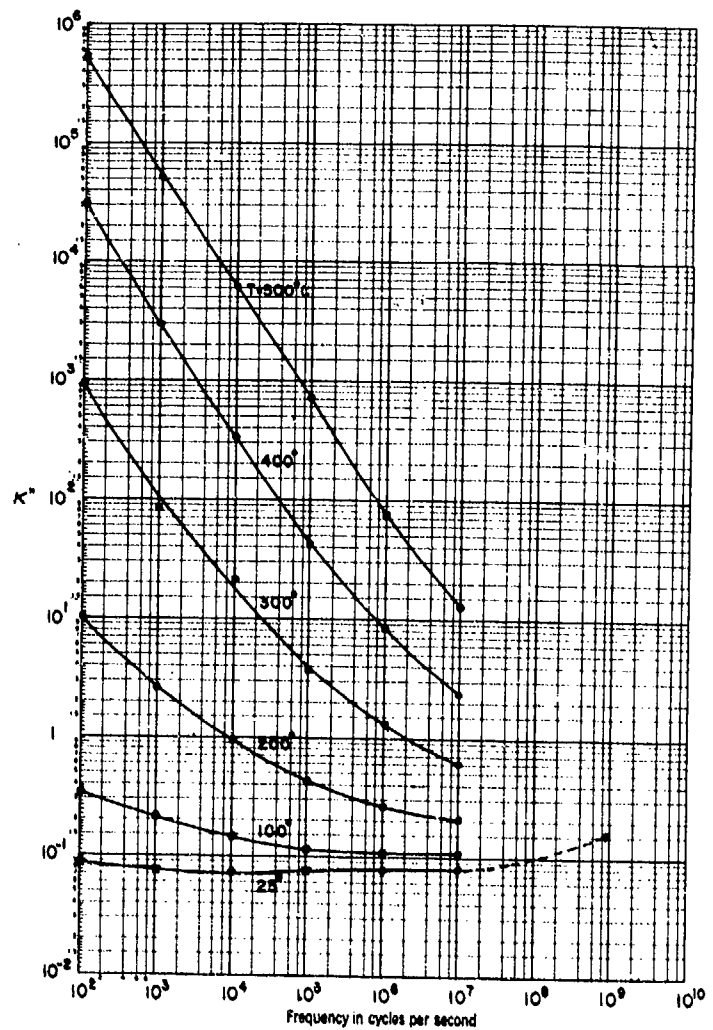
See also p. 121





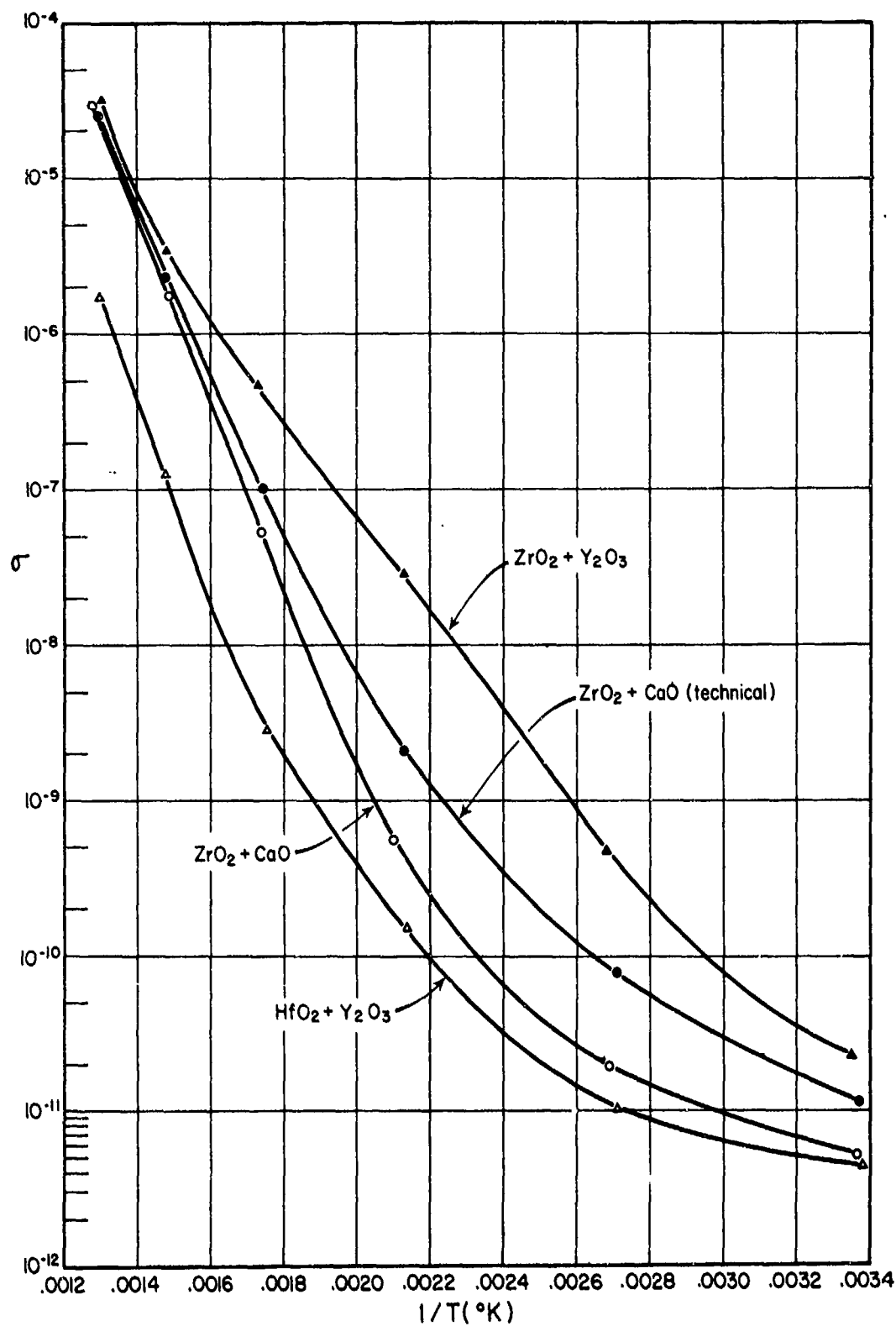
Zirconium oxide stabilized with 7.5% CaO, nuclear grade ceramic Zircoa Y-1362, densities of disk 5.087 g/cm<sup>3</sup>, of cylinder 5.015 g/cm<sup>3</sup>. Dielectric constant vs. frequency

Dielectric loss factor versus frequency.



See also p. 121

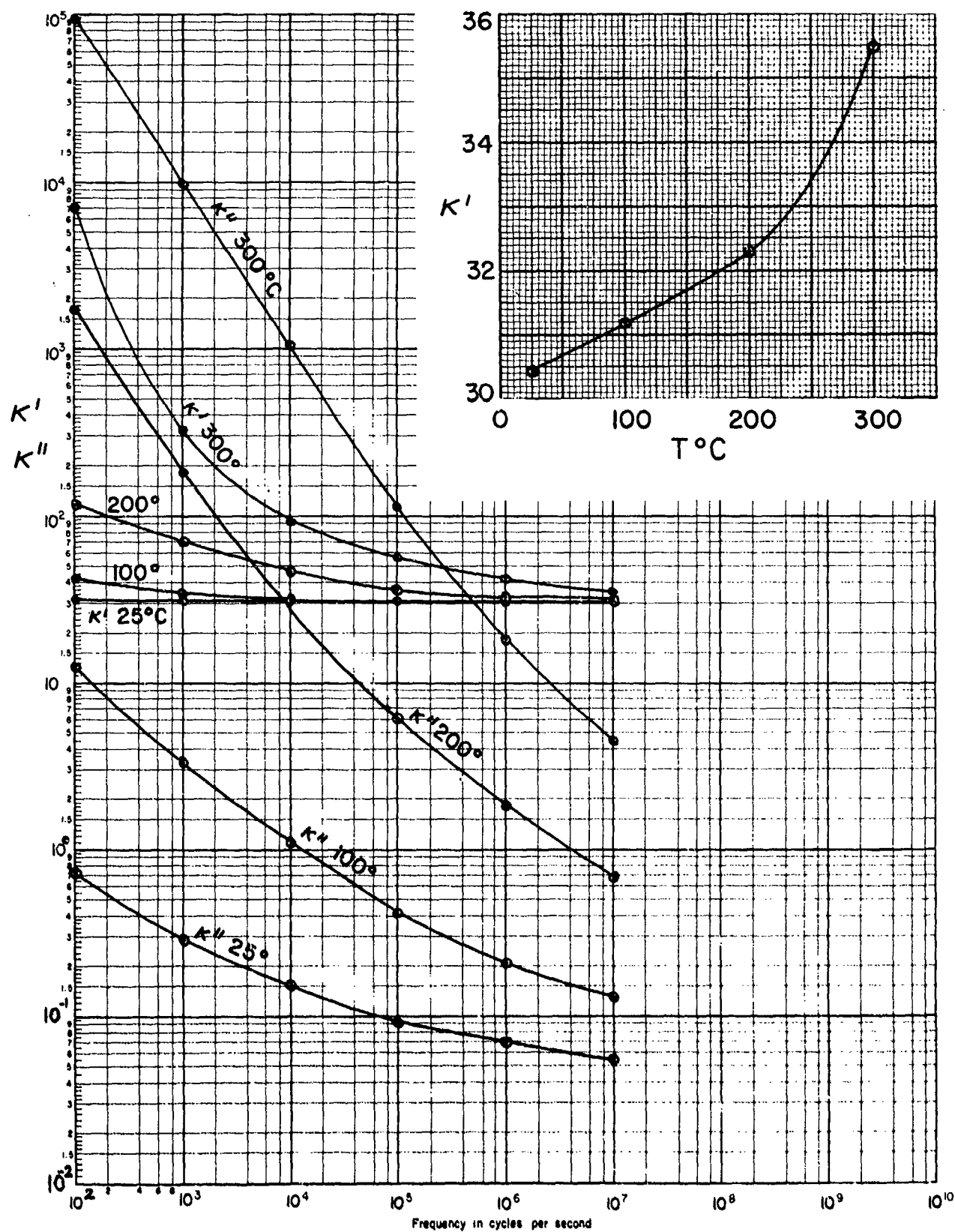
Zirconium oxide, nuclear grade, conductivity of heavy oxides at 100 Hz vs.  $1/T$ . Activation energies for each approach 1.25 eV.





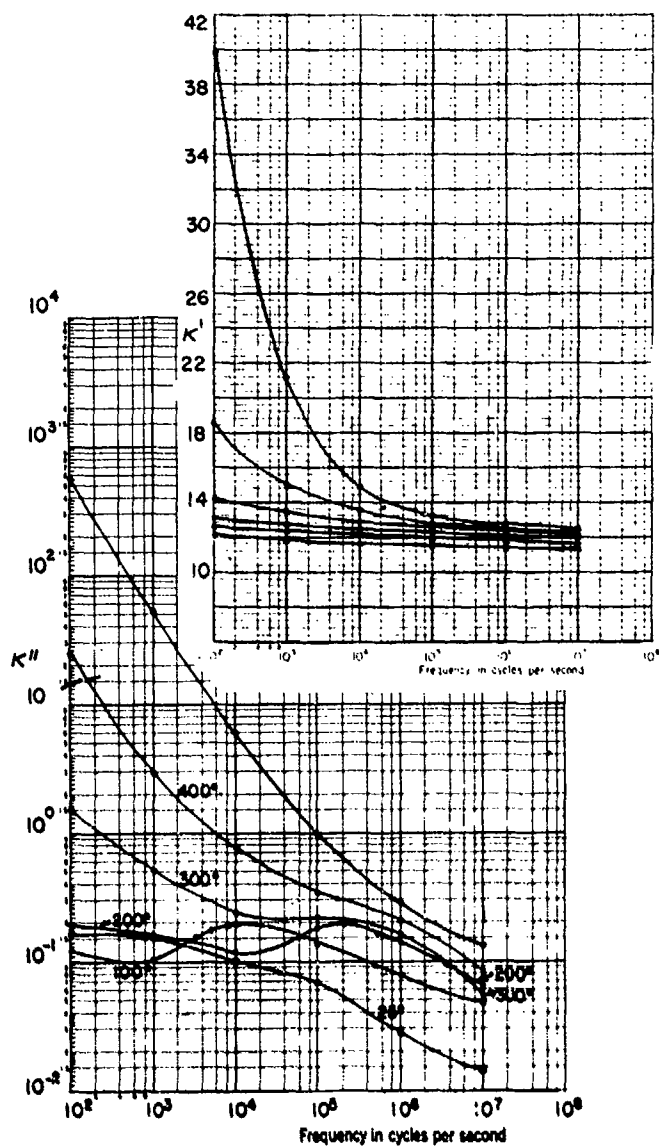
Zirconium oxide, "Zircolite" ceramic

Air Force Materials Laboratory  
Wright-Patterson Air Force  
Base, Ohio

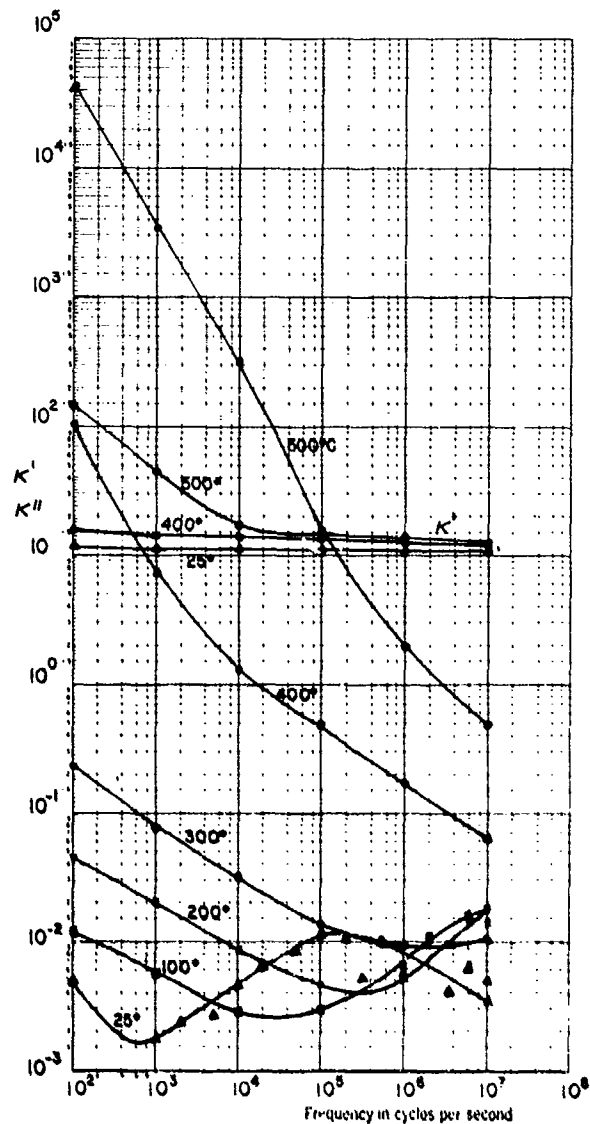


Zirconium silicate (zircon),  $\text{ZrSiO}_4$ ,  
single crystal, all samples from  
one crystal

E || c  
Sample 1, run 1,  
 $\text{N}_2$  to  $200^\circ\text{C}$ , air to  $500^\circ\text{C}$ ,  
Ag electrodes



E || c  
Sample 2, run 1,  
same conditions as for Sample 1

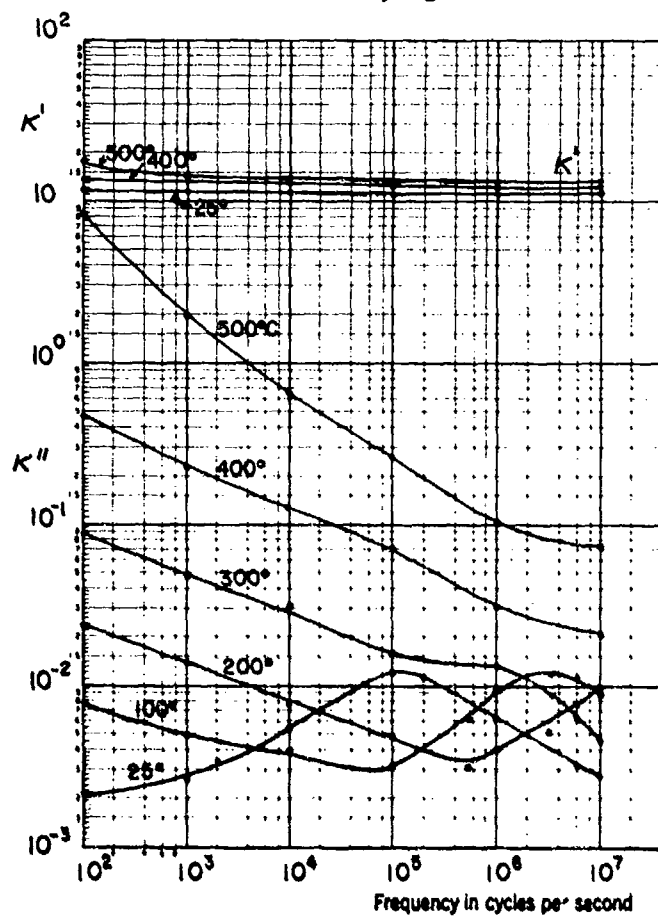


# Zircon (cont.)

E || c

Sample 2, run 2

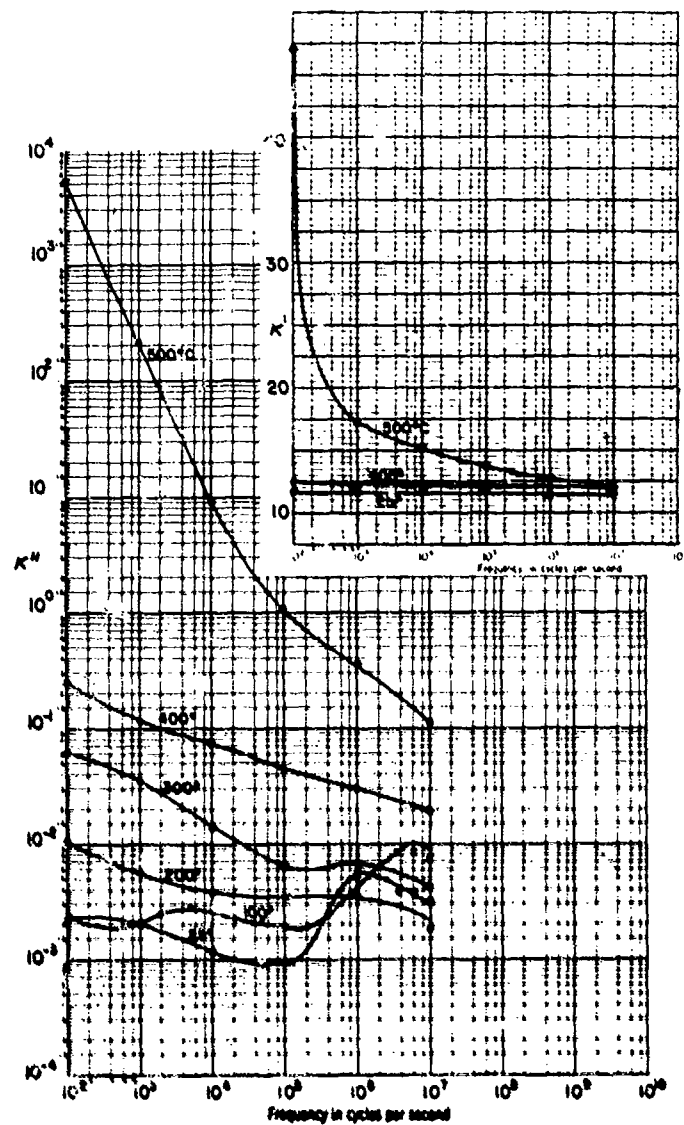
Argon atmosphere throughout the run, Ag electrodes



E ⊥ c

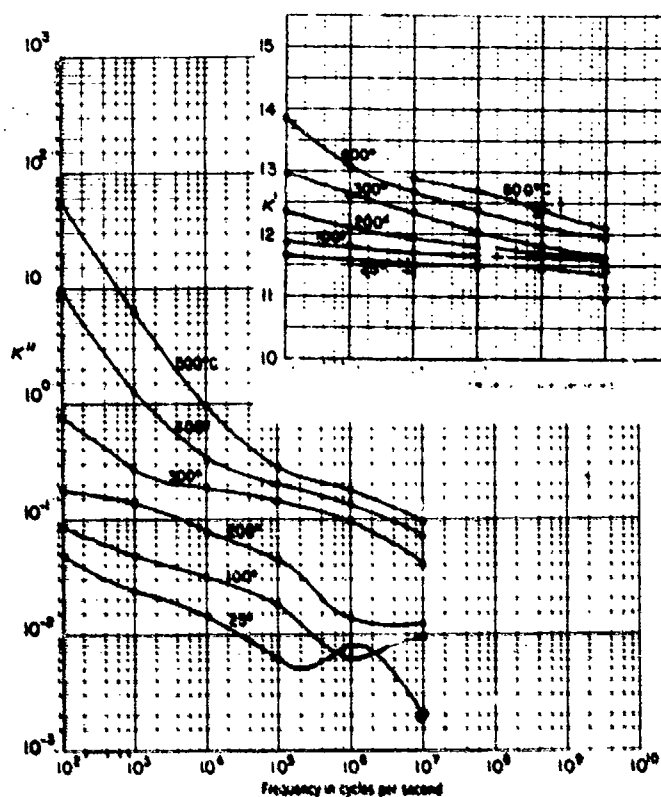
Sample 1, run 1

N<sub>2</sub> to 200°C, air to 500°C, Ag electrodes

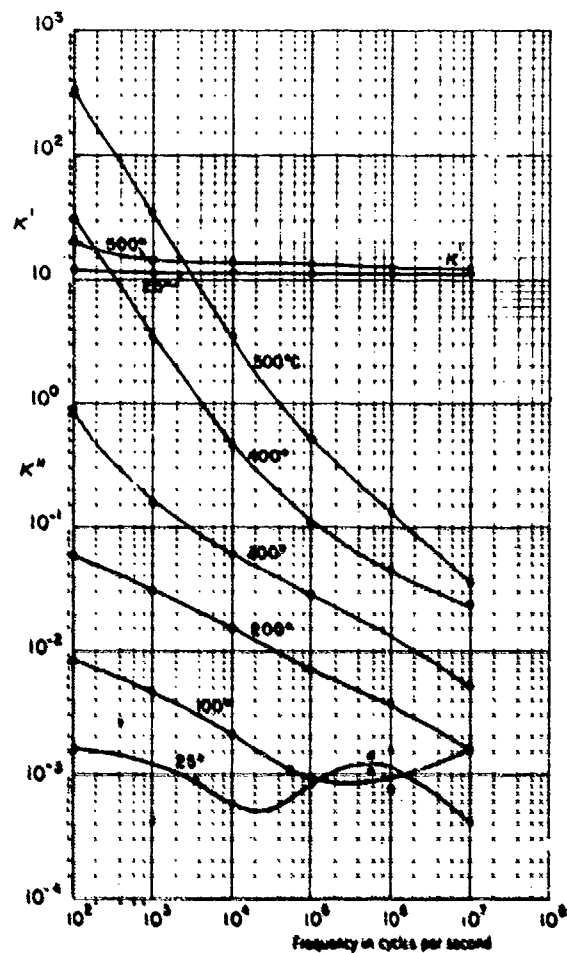


# Zircon (cont.)

$E \perp c$   
Sample 1, run 2  
 $N_2$  to  $500^\circ C$ , Ag electrodes



$E \perp c$   
Sample 1, run 3  
Air to  $500^\circ C$ , Pt electrodes



## II. MINERALS, ROCKS, SOILS, AND MISCELLANEOUS INORGANICS

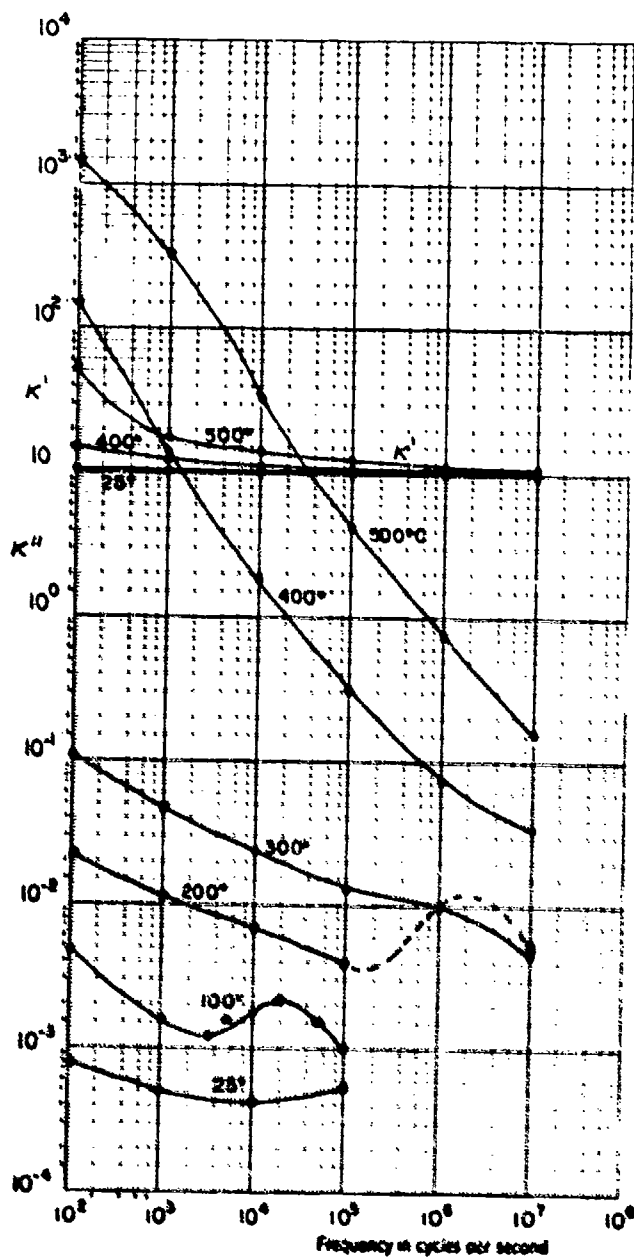
### Single-crystal minerals

Apatite

$E \perp c$

Sample 1, run 1, 25°C

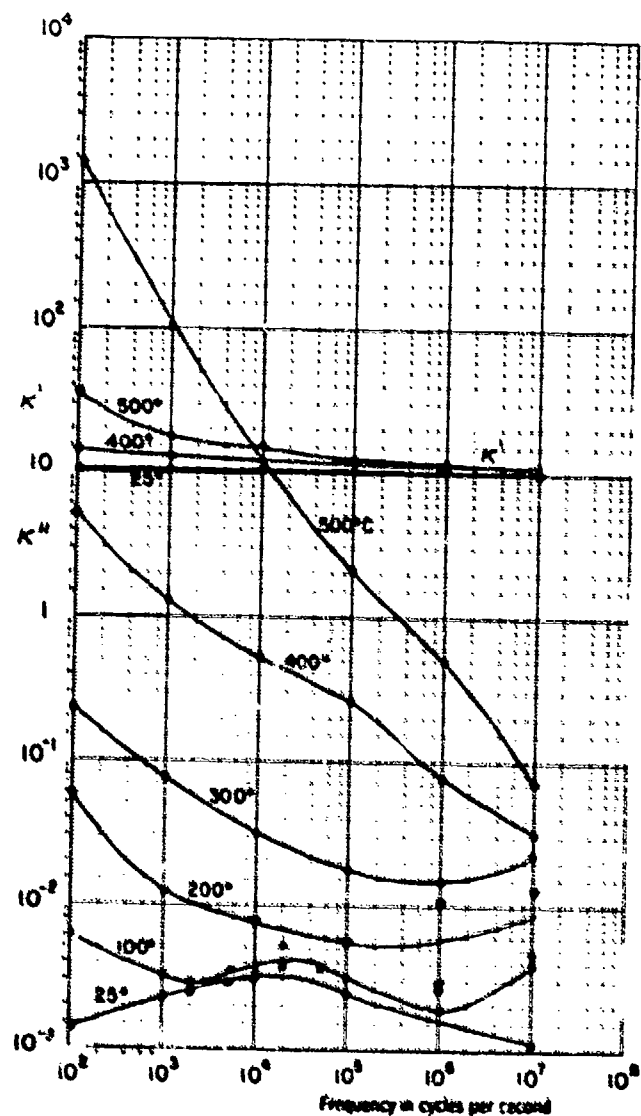
1 MHz,  $\kappa' = 10.1$



$E \perp c$

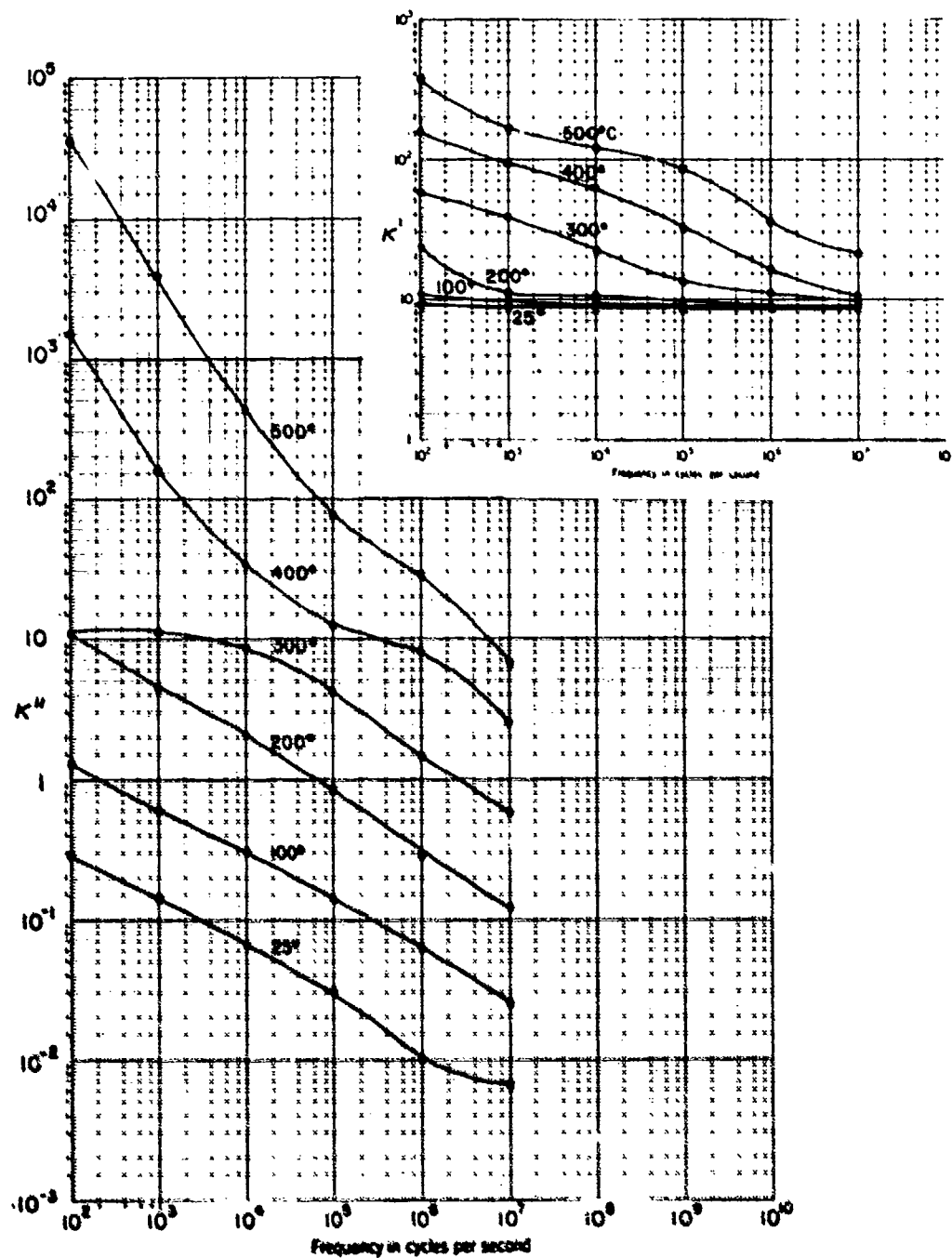
Sample 1, run 2,

repeat of run 1



Apatite (cont.)

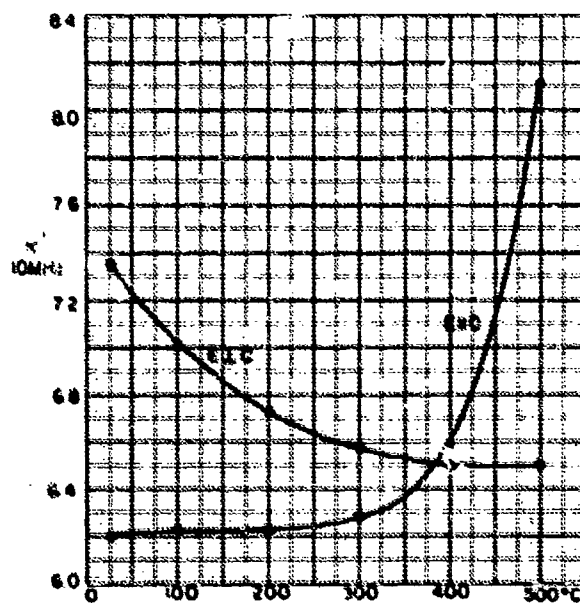
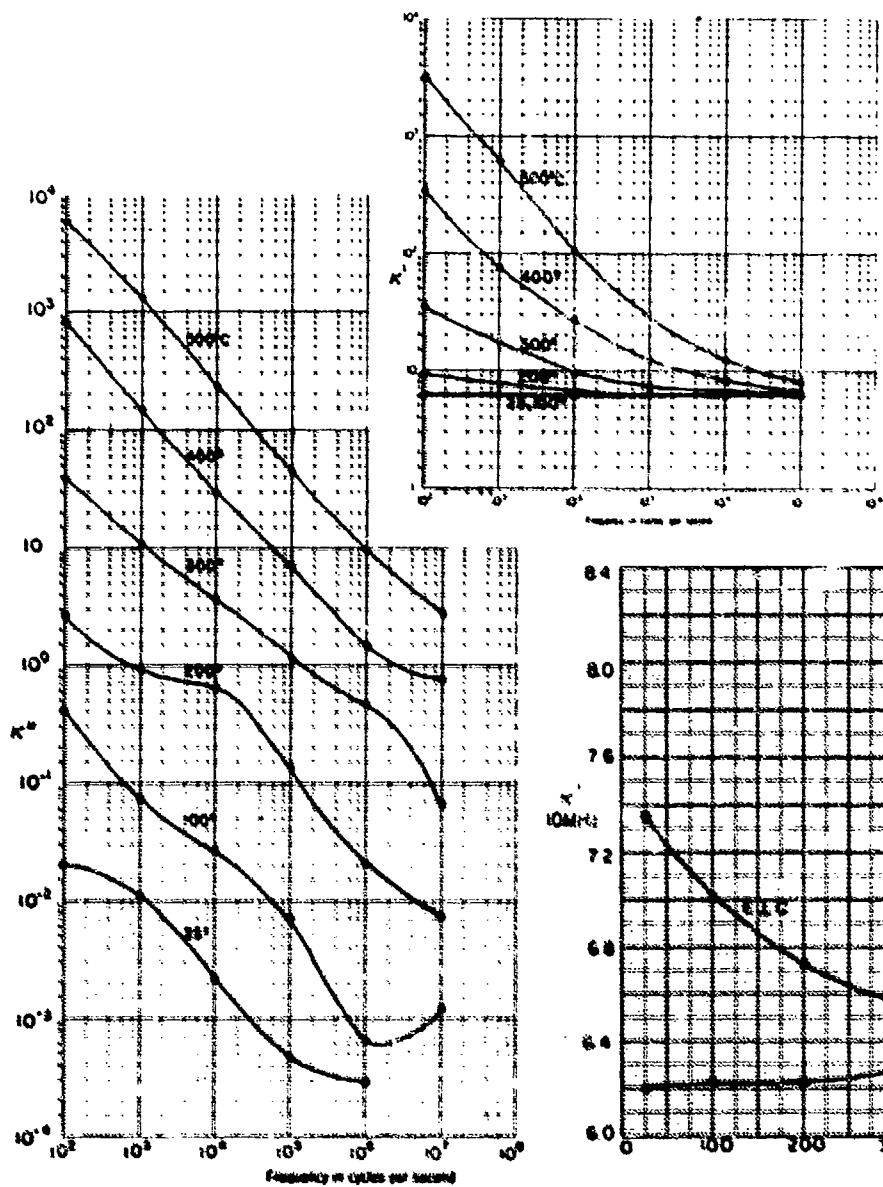
E || c, 25°C, 1 MHz,  $\kappa' = 8.58$



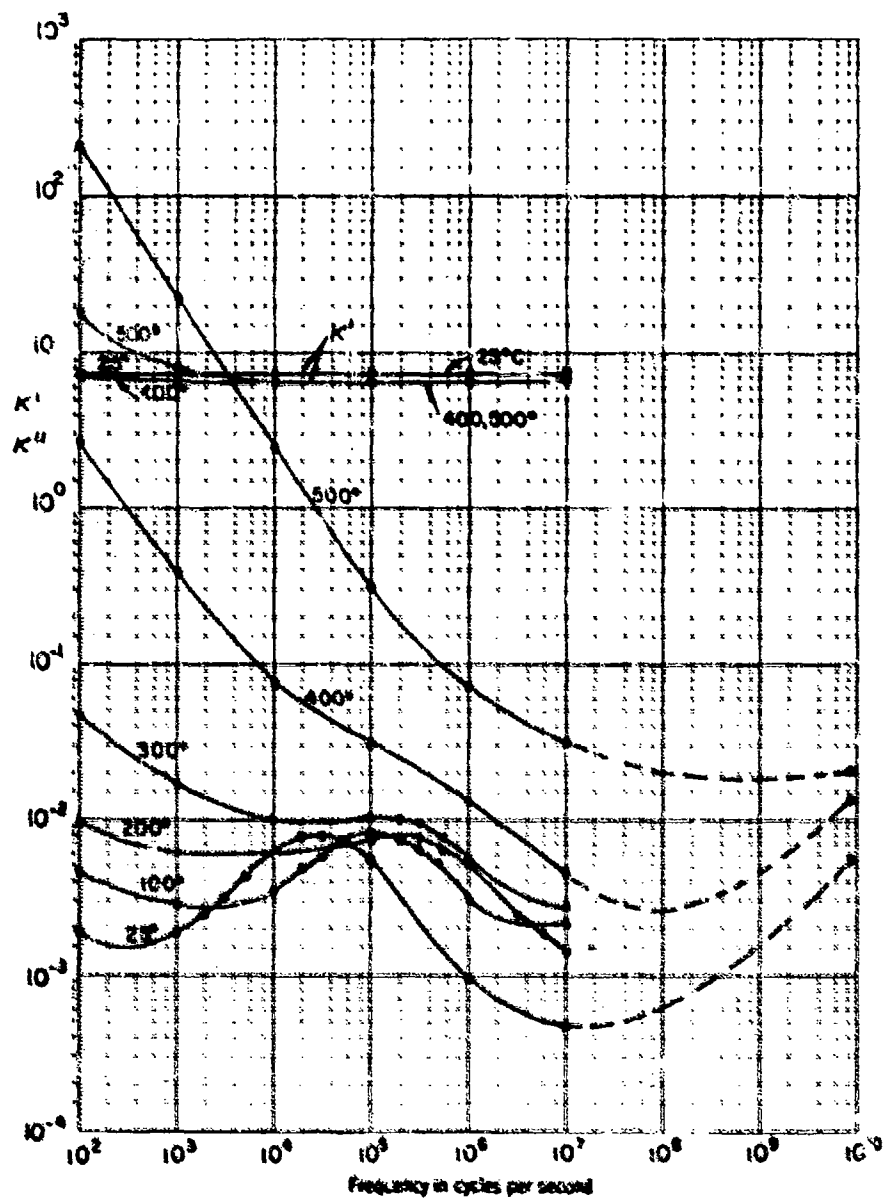
Astrophyllite Unoriented crystal		10 <sup>2</sup> Hz	10 <sup>3</sup> Hz	10 <sup>4</sup> Hz
		$\kappa'$ 15.42	15.17	14.83
	tan $\delta$	0.035	0.021	0.014
Benitoite BaTiS <sub>3</sub> O <sub>9</sub> . unoriented cryst.		$\kappa'$ 23.8	19.6	19.2
		tan $\delta$ 0.374	0.090	0.0195

Beryl

E || c



Beryl, E 1 c



Neptunite,  $(\text{Na}, \text{K})_2(\text{Fe}, \text{Mn})(\text{Si}, \text{Ti})_5\text{O}_{12}$   
data on unoriented crystal

	$10^3$ Hz	$10^4$ Hz
$\kappa'$	8.33	8.19
$\tan \delta$	0.0335	0.068

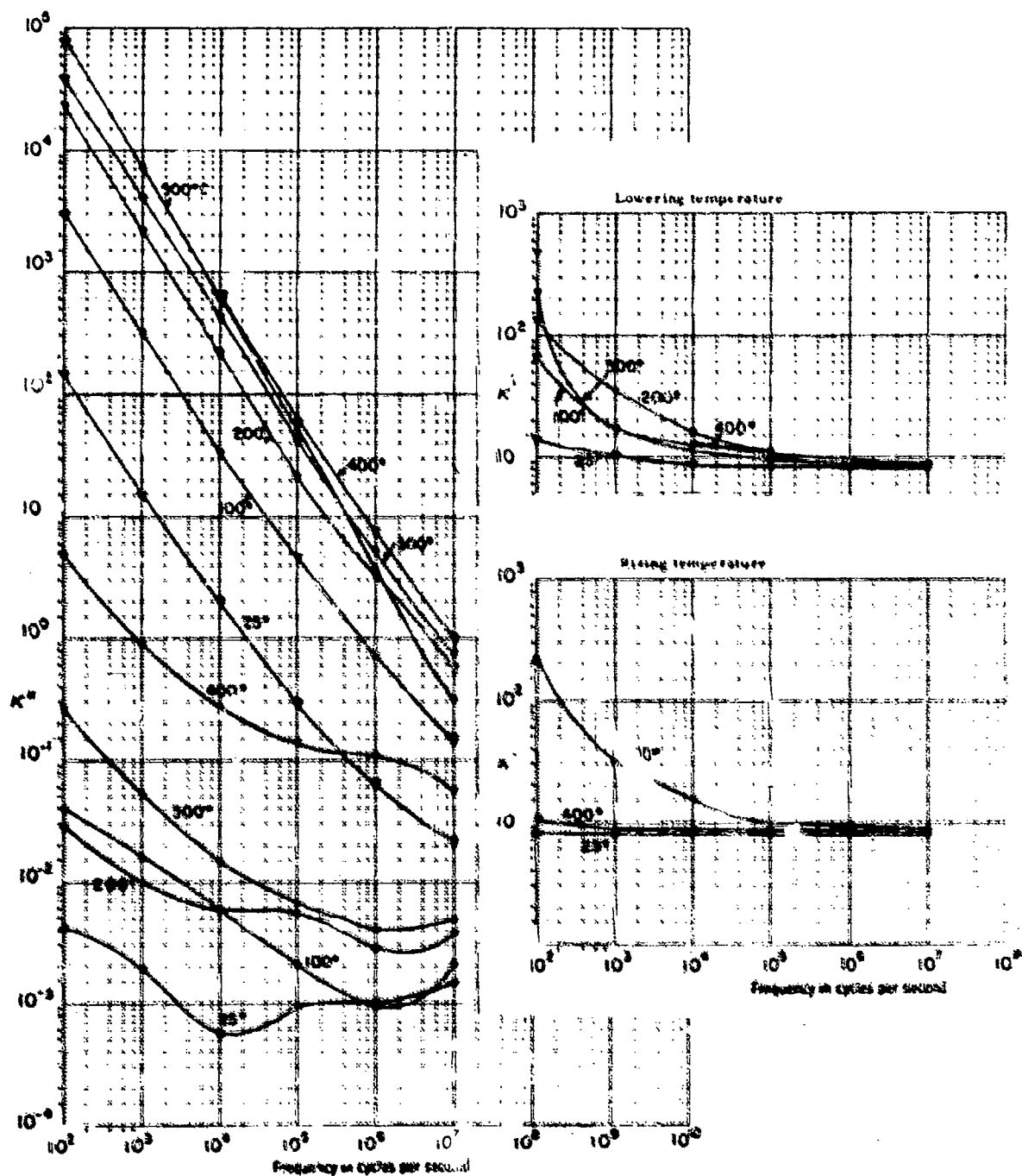


# Spodumene

E || a

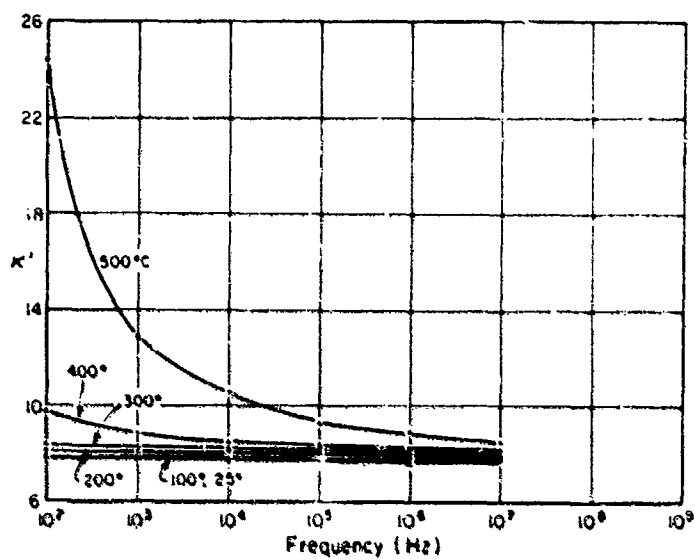
○ rising temperature

▽ lowering temperature

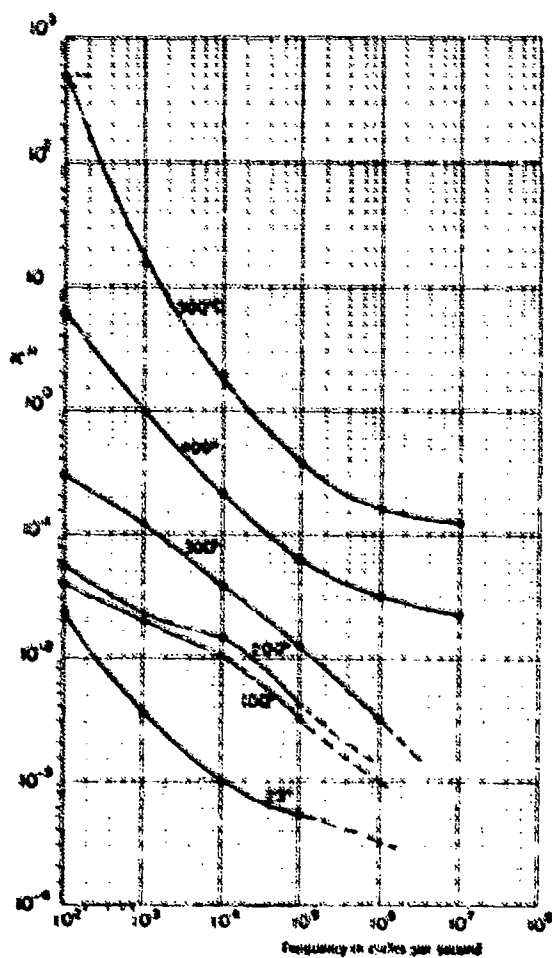


Spodumene (cont.)

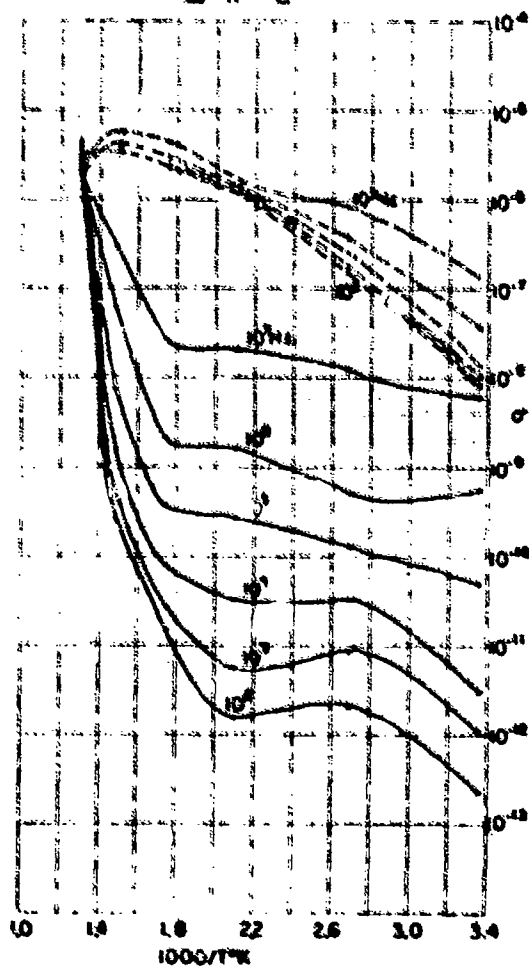
E || b



E || b

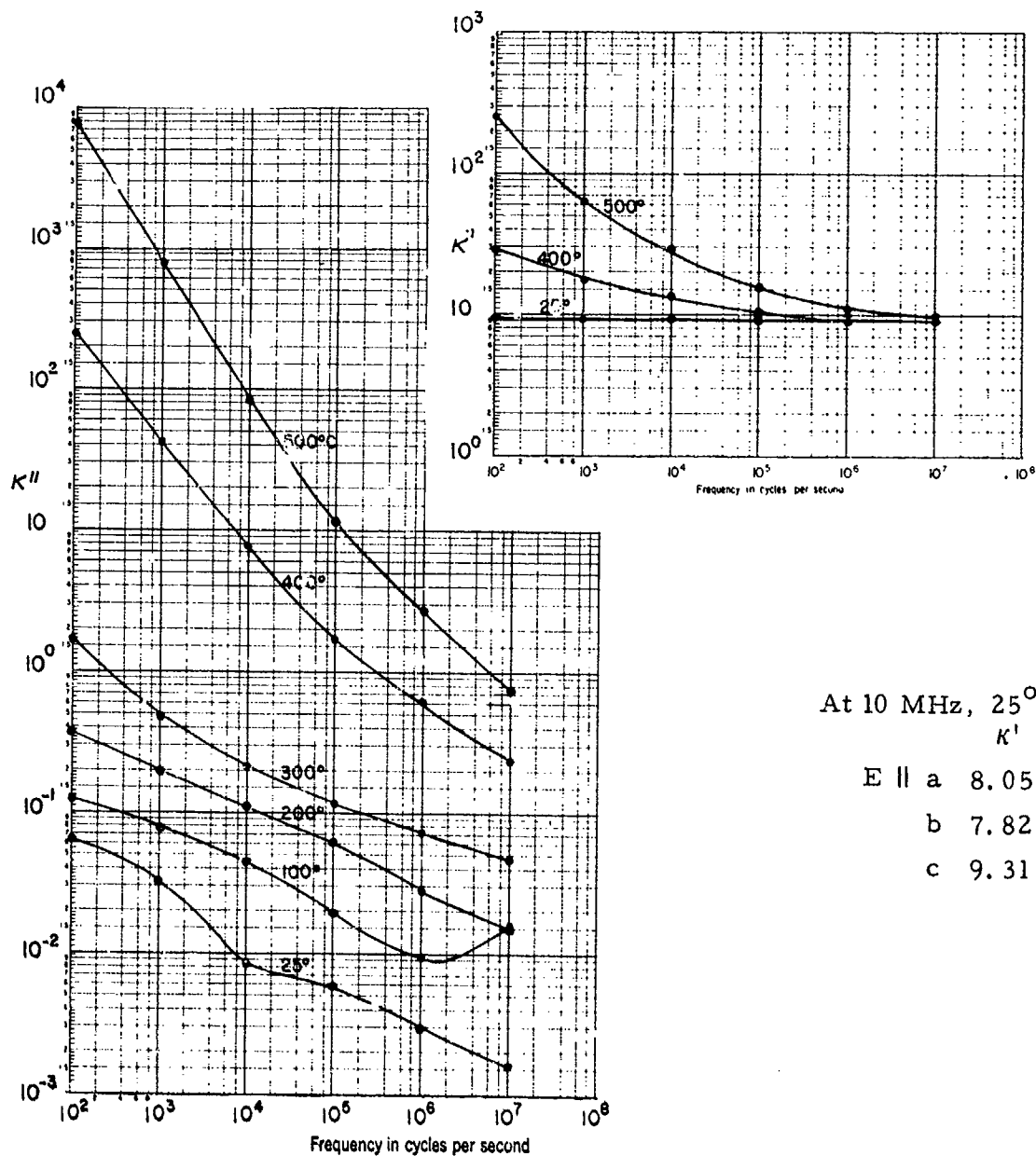


E || a



Spodumene (cont.)

E || c

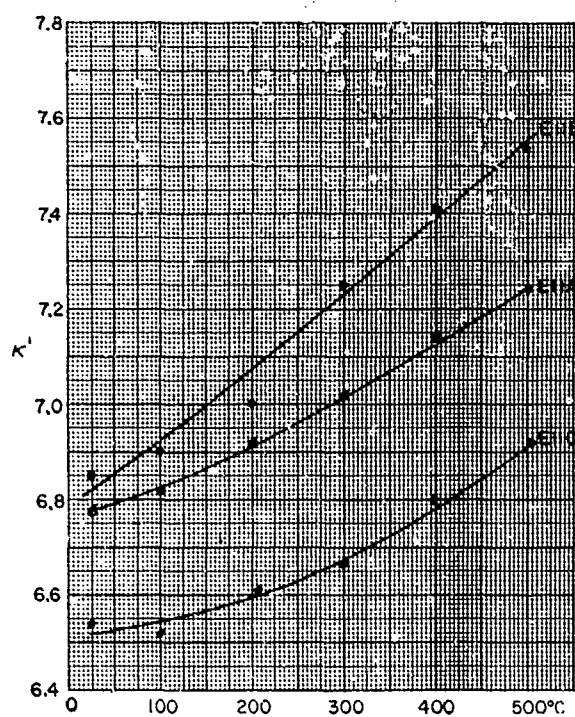


At 10 MHz, 25°C  
 $K'$

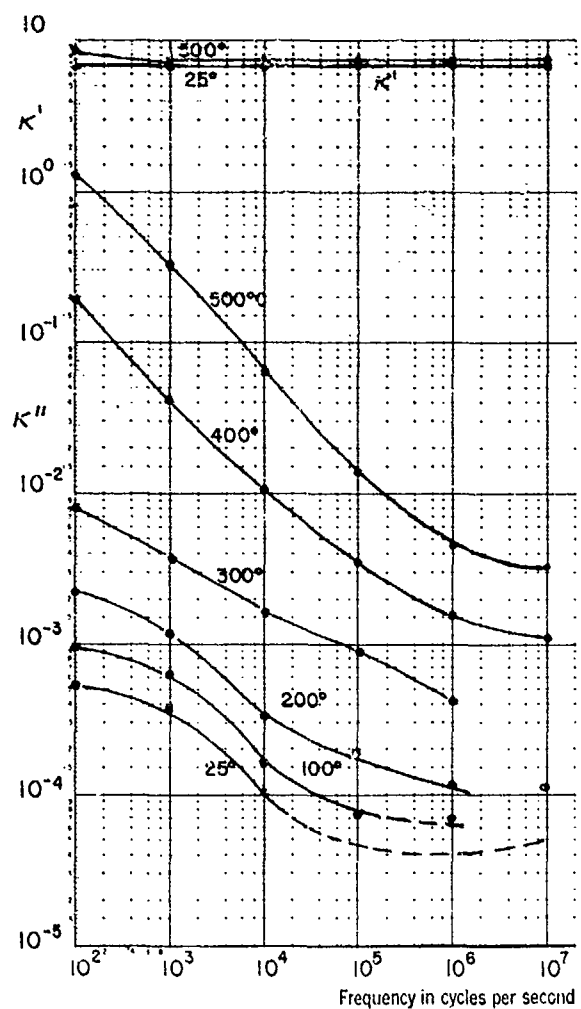
E || a 8.05  
b 7.82  
c 9.31

Topaz

$\kappa''$  at 10 MHz

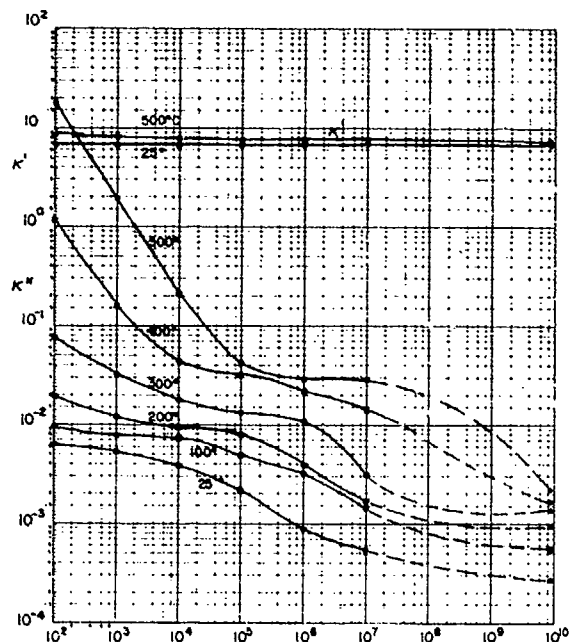


E || a

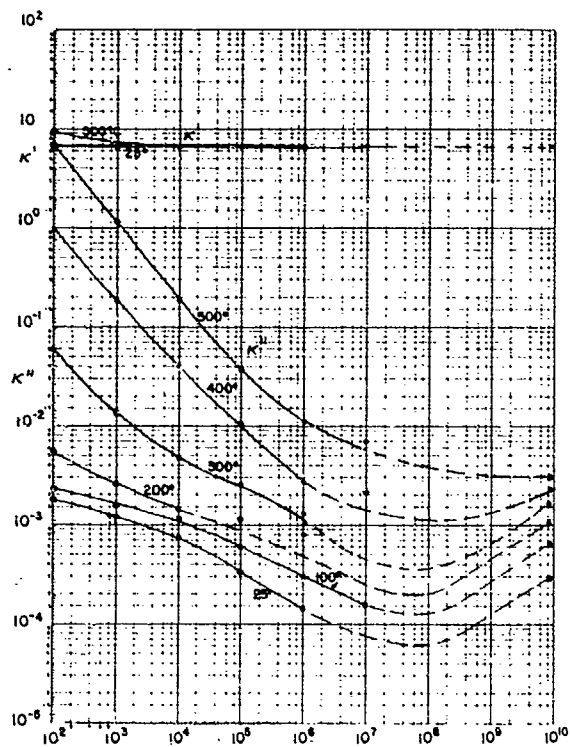


# Topaz (cont.)

$E \parallel b$

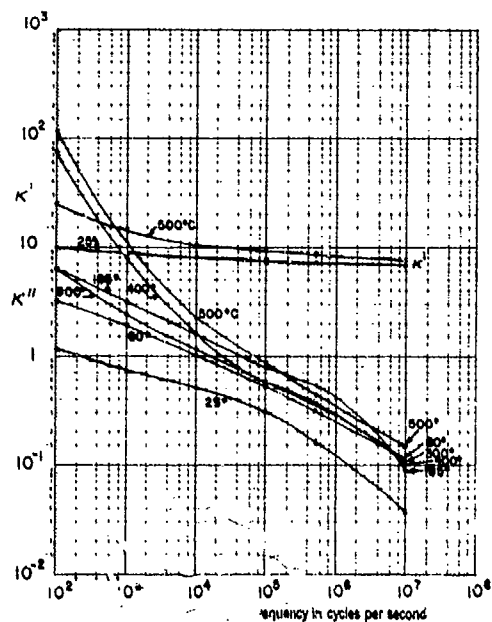


$E \parallel c$

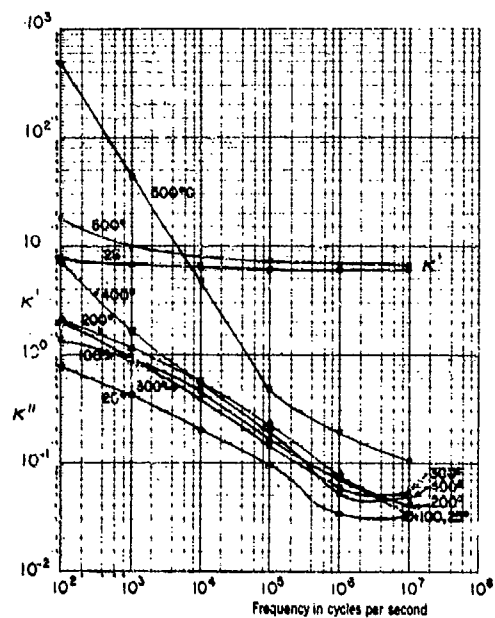


## Tourmaline

$E \perp c$ , piezoelectrically active  
at 1 MHz



$E \parallel c$



# Crushed minerals

Halite (rock-like pieces of porous salt), at 50% R.H., 25°C, 14 GHz

Sample	$\kappa'$	$\tan \delta$	Density (g/cm <sup>3</sup> )
1, surface	4.52 - 4.63	.0056 - .0057	1.808
2, "	4.68 - 4.82	.0106 - .0103	1.861
3, "	3.81 - 3.83	.0127 - .0109	1.565
4, "	3.95 - 4.00	.0104 - .0134	1.670
5, 1' down	3.69 - 3.94	.0198 - .0125	1.500
6, "	3.25 - 3.50	.0077 - .0113	1.422
7, 3' "	4.17 - 4.18	.036 - .046	1.646
7, dried	4.12 - 4.19	.0193 - .0206	1.640

Limonite, crushed, density 1.733 g/cm<sup>3</sup>

Harvard College Observatory

T°C	$\kappa'$	$\tan \delta$	$\kappa'$	$\tan \delta$
25	4.17	.0108	3.73	.046
475	3.65	.0134	3.63	.0193
404	3.62	.0076	3.60	.0113
325	3.61	.0057	3.58	.0084
250	3.61	.0048	3.57	.0073
185	3.60	.0045	3.56	.0064
107	3.58	.0047	3.55	.0059
22	3.56	.0057	3.53	.0055

Sample in equilibrium with room humidity approx. 50%.

Limonite, 8.52 GHz

Sample 1, coarse, 25°C

$\kappa' = 3.95 - 4.01$  depending on rotation  
 $\tan \delta = 0.18 - 0.059$

Sample 2, fine, 25°C

$\tan \delta = 0.0122 - 0.0127$

Sample 3	T°C	$\kappa'$	$\tan \delta$
	25	3.82	.0012
	510	3.60	.0085
	400	3.55	.0047
	300	3.52	.0039
	200	3.50	.0042
	100	3.48	.0043
	25	3.49	.0043

Magnesite, crushed powder, hard-packed

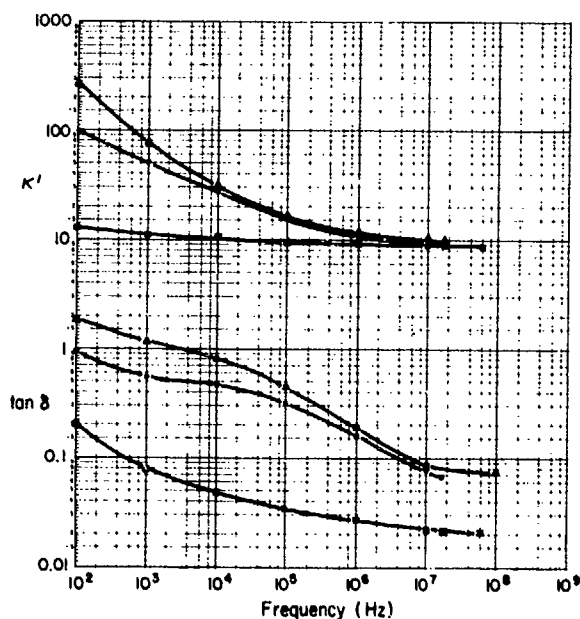
25°C, 50% R.H., 8.52 GHz,  $\kappa' = 3.29$ ,  $\tan \delta = .0054 - .0059$ , density 1.11 g/cm<sup>3</sup>

Quartz powder, 8.52 GHz, pre-dried in oven at 100°C, density 1.22 g/cm<sup>3</sup>

T°K	$\kappa'$	$\tan \delta$
80	2.446	.0021
200	2.460	.0027
300	2.472	.0028
400	2.483	.0027
500	2.495	.0031
600	2.497	.0035

# Rocks

## Hawaiian high-density basalt

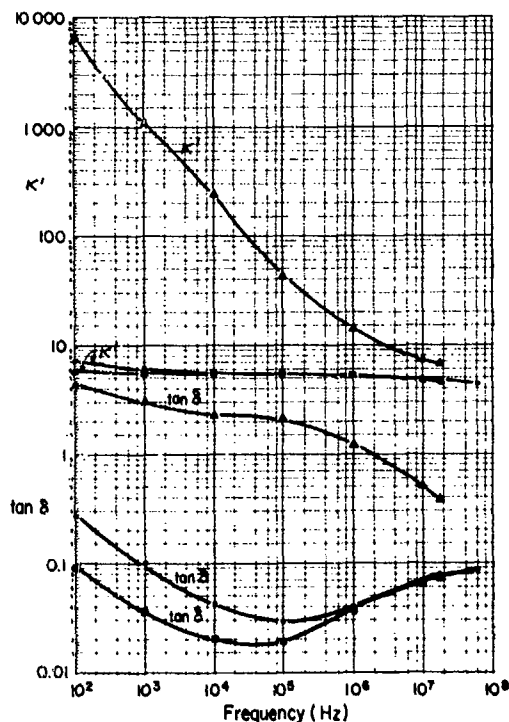


- % H<sub>2</sub>O on dry weight basis 0.358  
% H<sub>2</sub>O on dry volume basis 0.956  
density 2.6756 g/cm<sup>3</sup>
- Dry after 3 days in oven at 105°C  
density 2.669 g/cm<sup>3</sup>
- ▲ % H<sub>2</sub>O on dry weight basis 0.377  
% H<sub>2</sub>O on dry volume basis 1.005  
density 2.677 g/cm<sup>3</sup>

## Hawaiian high-density basalt 50% relative humidity

	Density 2.717 g/cm <sup>3</sup>					
	Sample 1	Sample 2	Sample 3	Sample 3	Sample 3	Sample 4
Freq. (Hz)	3x10 <sup>8</sup>	10 <sup>7</sup>	3x10 <sup>8</sup>	10 <sup>9</sup>	3x10 <sup>9</sup>	8.5x10 <sup>9</sup>
κ	8.36	9.90	9.30	9.08	8.85	8.40
tan δ	.043	.080	.034	.033	.037	.04
μ'/μ <sub>o</sub>	1.174	1.17	1.113	1.10	1.08	1.01
tan δ <sub>m</sub>	.0077	<.002	.0075	.026	.072	.06

# Hawaiian low-density basalt



- %  $H_2O$  on dry weight basis 0.441  
%  $H_2O$  on dry volume basis 0.0617  
density  $1.401 \text{ g/cm}^3$
- Dry (after 3 days in oven at  $105^\circ\text{C}$ )  
density  $1.400 \text{ g/cm}^3$
- ▲ %  $H_2O$  on dry weight basis 2.71  
%  $H_2O$  on dry volume basis 3.79  
density  $1.438 \text{ g/cm}^3$

## Hawaiian low-density basalt 50% relative humidity

Freq. (Hz)	$10^7$	$3 \times 10^8$	$10^9$	$3 \times 10^9$
$K$	4.9	3.74	3.51	3.30
$\tan \delta$	.068	.085	.0481	.053
$\mu'/\mu_o$	1.047	1.047	1.040	1.035
$\tan \delta_m$	<.002	.0040	.002	.002

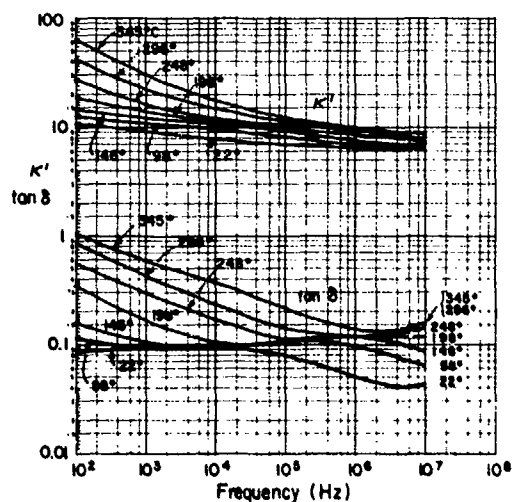
## Hawaiian deep-ocean basalt No change after heating to $200^\circ\text{C}$

Freq. (Hz)	$10^5$	$10^6$	$10^7$	$8.5 \times 10^9$
$K$	188	153	124	10.2
$\tan \delta$	93.5	11.6	.146	.560
$\rho$	1025	1015	995	36.9



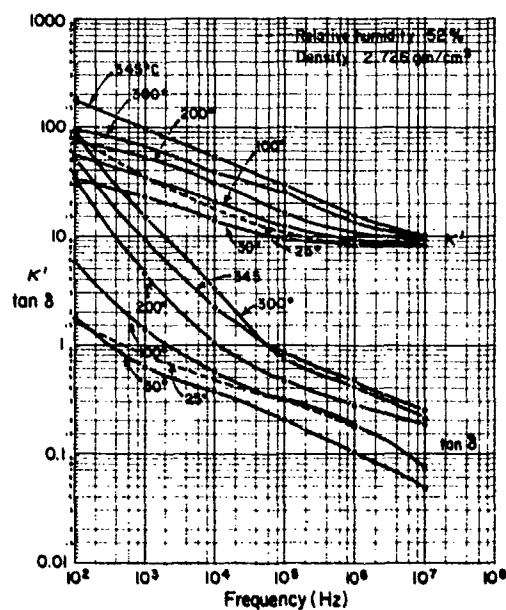
# Quincy granite

Density 2.631 g/cm<sup>3</sup>  
Temp. run in dry N<sub>2</sub>



# Virginia granite or marble

Temperature run in dry N<sub>2</sub>



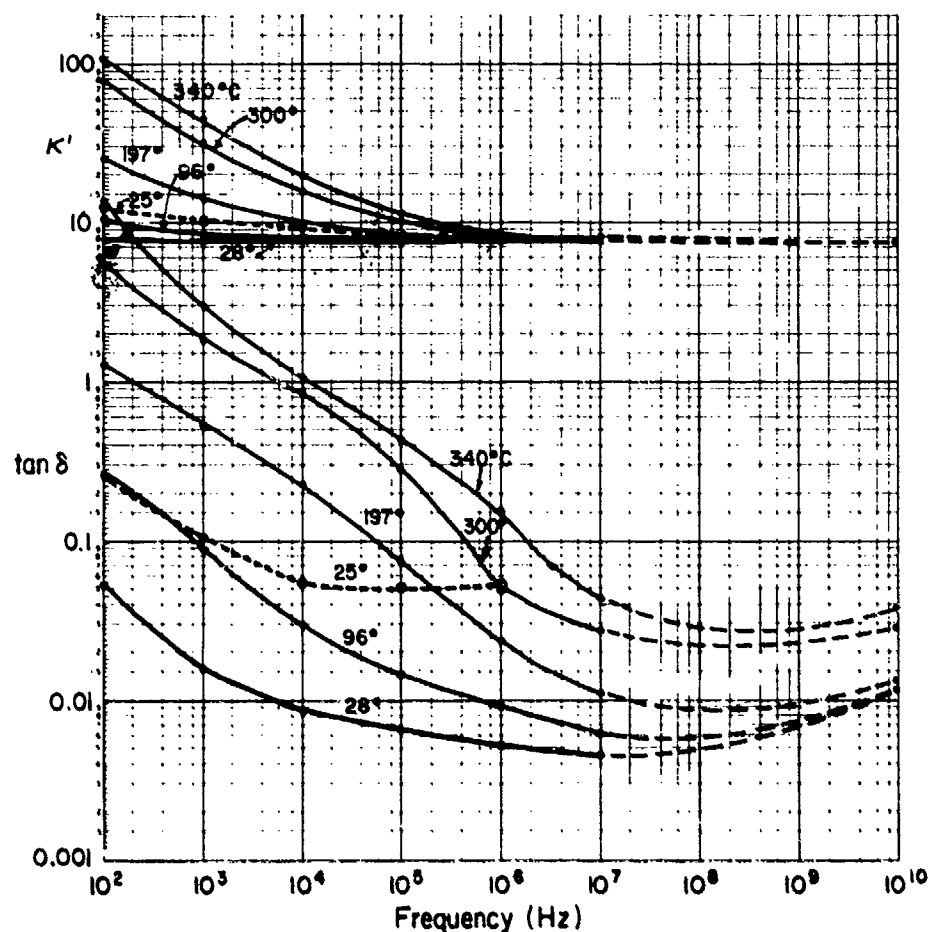
# Quincy granite

T°C	10 <sup>2</sup> Hz	10 <sup>3</sup> Hz	10 <sup>4</sup> Hz	10 <sup>5</sup> Hz	T°C	1 kHz	σ
25	κ' 10.5	9.26	8.01	2.06	26	9.26	4.50 × 10 <sup>-10</sup>
	tan δ 0.0796	0.0875	0.0875	0.0705	69	10.3	4.58
	σ 4.64 × 10 <sup>-11</sup>	4.5 × 10 <sup>-10</sup>	3.9 × 10 <sup>-10</sup>	2.76 × 10 <sup>-8</sup>	105	10.9	4.64
200	κ' 15.4	12.47	11.07	9.78	147	11.5	5.31
	tan δ 0.21	0.121	0.088	0.090	204	12.51	8.61 × 10 <sup>-10</sup>
	σ 1.797 × 10 <sup>-10</sup>	8.37 × 10 <sup>-10</sup>	5.40 × 10 <sup>-9</sup>	4.88 × 10 <sup>-8</sup>	251	14.87	1.85 × 10 <sup>-9</sup>
400	κ' 64.5	32.9	19.42	12.86	305	19.3	3.38 × 10 <sup>-9</sup>
	tan δ 1.02	0.60	0.374	0.252	345	23.4	5.51 × 10 <sup>-9</sup>
	σ 3.65 × 10 <sup>-9</sup>	1.097 × 10 <sup>-8</sup>	4.03 × 10 <sup>-8</sup>	1.797 × 10 <sup>-7</sup>	400	32.9	1.09 × 10 <sup>-8</sup>
600	κ' 293	106	42.5	22.0	466	34.4	9.5 × 10 <sup>-8</sup>
	tan δ 6.85	2.31	1.03	0.94	553	81.3	9.34 × 10 <sup>-8</sup>
	σ 1.114 × 10 <sup>-7</sup>	1.16 × 10 <sup>-9</sup>	2.43 × 10 <sup>-7</sup>	6.60 × 10 <sup>-7</sup>	601	106	1.16 × 10 <sup>-9</sup>
800	κ' 4195	238	84	37.4	700	172	4.25 × 10 <sup>-7</sup>
	tan δ 14.4	9.64	3.05	1.11	806	243	1.311 × 10 <sup>-6</sup>
	σ 1.116 × 10 <sup>-6</sup>	1.275 × 10 <sup>-6</sup>	1.423 × 10 <sup>-6</sup>	2.30 × 10 <sup>-6</sup>	874	26,800	1.84 × 10 <sup>-4</sup>
1000	κ' 47000	6100	710	12.4	996	45,900	3.57 × 10 <sup>-4</sup>
	tan 14.0	12.6	12.4				
	σ 3.65 × 10 <sup>-4</sup>	4.26 × 10 <sup>-4</sup>	4.89 × 10 <sup>-4</sup>				

Virginia Greenstone

Density  $2.936 \text{ g/cm}^3$ , temperature run in dry  $\text{N}_2$

(-----) R. H. 52%



Limestone, from Lucerne Valley

50% R. H.,  $25^\circ\text{C}$ , 14 GHz

Raytheon

Sample	$K'$	$\tan \delta$	Density
1	8.21 - 8.45	.0038 - .0080	2.667
2	8.62 - 8.64	.0178 - .0189	2.646

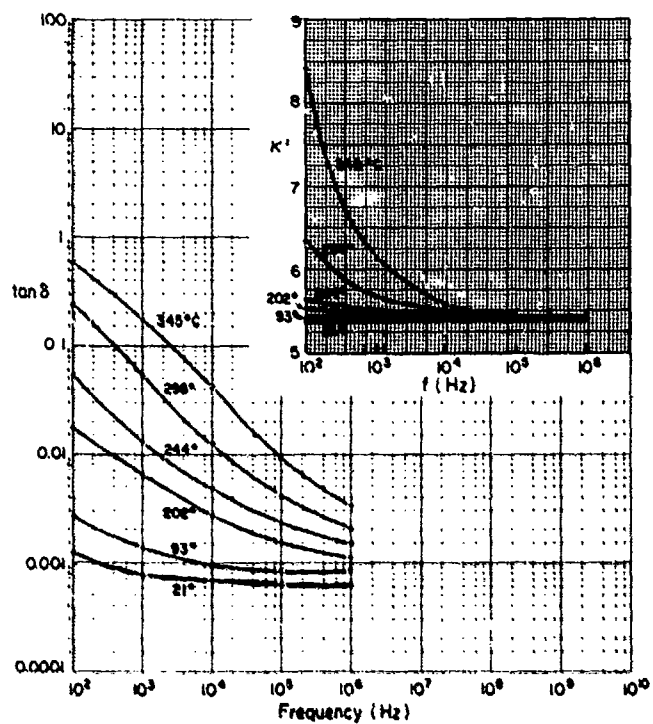
Synthetic basalt and lunar rocks, Apollo 11 and 12, see:

- D.H. Chung, W. B. Westphal, and G. Simmons, "Dielectric Properties of Apollo 11 Lunar Samples and their Comparison with Earth Materials," J. Geophys. Res. 75, 6524-6531 (1970).
- D. H. Chung, W. B. Westphal, and G. Simmons, "Dielectric Properties of Apollo 12 Lunar Samples," a paper (T64c) presented at the 1970 Am. Geophys. Union Meeting, Washington D.C., April 23, 1970.
- D. H. Chung, W. B. Westphal, and G. Simmons, Dielectric Behavior of Lunar Samples: Electromagnetic Probing of the Lunar Interior," Proc. Second Lunar Sci. Conf., Vol. 3, MIT Press, 1971, pp. 2381-2390.

# Rocks (cont.)

## Rhyolite

Density 2.655 g/cm<sup>3</sup>, temperature run in dry N<sub>2</sub>



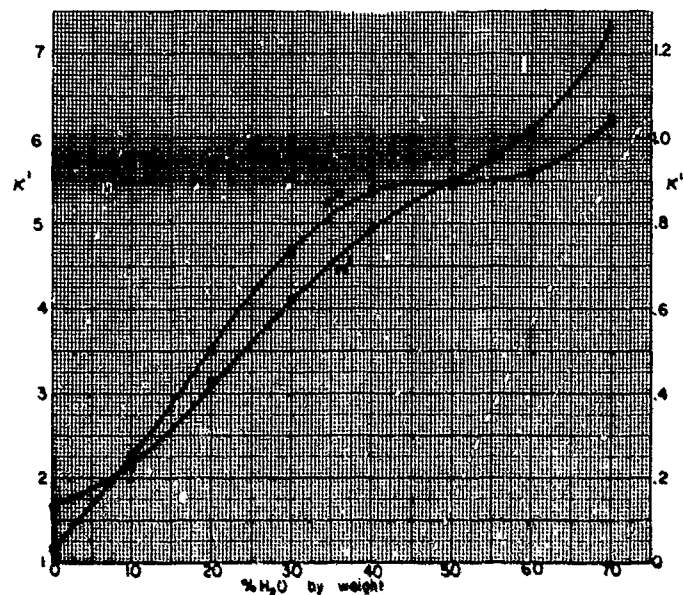
Sandstone, almond, oil-bearing as cored, 25°C

Raytheon

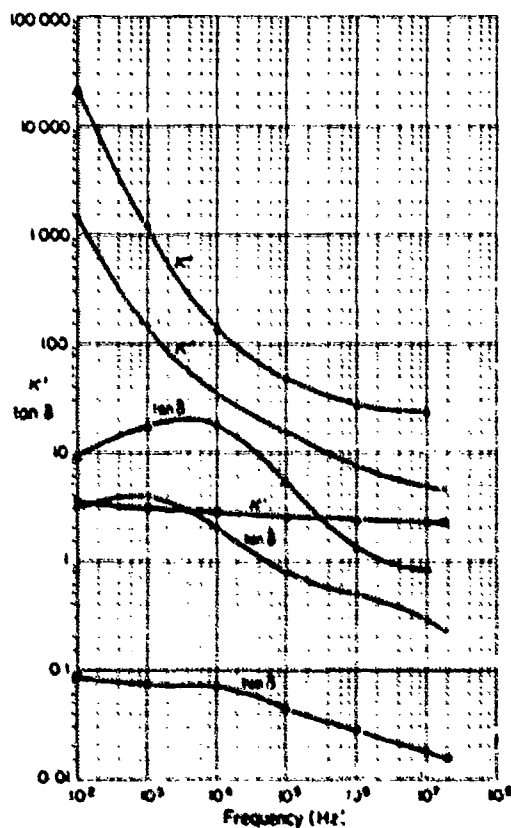
## Frequency in MHz

Sample		1	3	10	60	100
1	$\kappa'$	5.64	5.23	4.90	4.55	4.50
	$\tan \delta$	0.131	0.104	0.084	0.059	0.049
2	$\kappa'$	6.13	6.09	6.07	6.06	6.06
	$\tan \delta$	0.0100	0.0084	0.0059	0.0047	0.0051
3	$\kappa'$	6.05	6.04	6.01	5.91	5.87
	$\tan \delta$	0.0068	0.0079	0.00855	0.0095	0.0097
4	$\kappa'$	5.33	5.08	4.92	4.75	4.73
	$\tan \delta$	0.060	0.057	0.051	0.036	0.027
5	$\kappa'$	5.40	5.16	4.93	4.68	4.61
	$\tan \delta$	0.080	0.068	0.058	0.042	0.032
6	$\kappa'$	22.9	11.24	9.20	6.60	6.20
	$\tan \delta$	1.88	1.39	0.68	0.338	0.29
7	$\kappa'$	6.15	6.12	6.10	6.04	6.00
	$\tan \delta$	0.0088	0.0093	0.0096	0.0102	0.0105

Soils  
Fullers Earth, at 8.52 GHz



Hawaian



- % H<sub>2</sub>O on weight basis
- % H<sub>2</sub>O on volume basis
- Density 0.8634 g/cm<sup>3</sup>
- Dry after 3 days in oven at 105°C
- Density .7627 g/cm<sup>3</sup>
- ▲ % H<sub>2</sub>O on dry weight basis = 72.27
- % H<sub>2</sub>O on volume basis = 50.60
- Density 1.2133 g/cm<sup>3</sup>

# Soils

Hawaiian soil saturated with distilled  $H_2O$

%  $H_2O$  on dry weight basis = 127.5

%  $H_2O$  on volume basis = 63.0

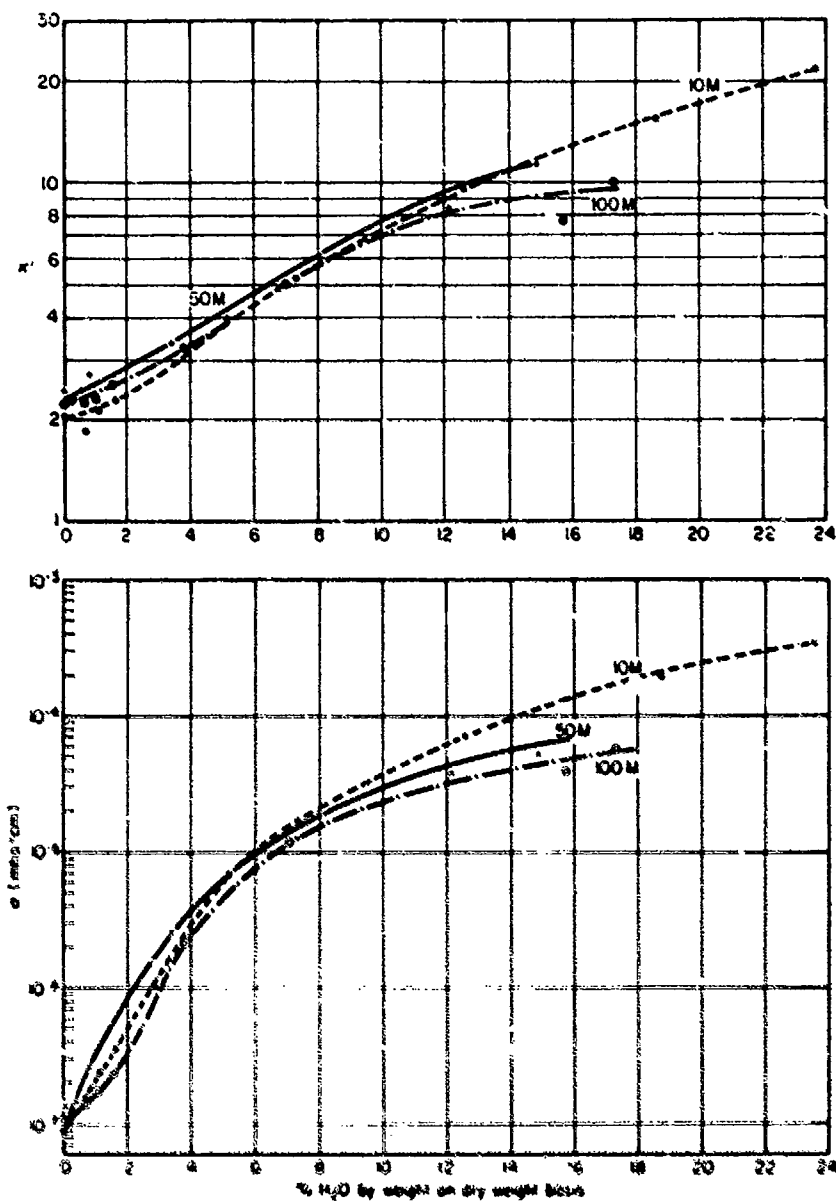
Density  $1.303 \text{ g/cm}^3$

Freq. (Hz)	$10^3$	$10^4$	$10^5$	$10^6$	$9.5 \times 10^6$	$7 \times 10^7$
$\kappa$	29,700	988	230	1295	81.5	64.2
$\tan \delta$	135	43.9	20.05	3.32	.776	.185

Hawaiian soil with approximately 25%  $H_2O$   
on dry weight basis. Density  $\approx .88 \text{ g/cm}^3$ .

Freq. (Hz)	$10^2$	$10^3$	$10^4$	$10^5$	$10^6$	$10^7$	$3 \times 10^8$	$1 \times 10^9$	$3 \times 10^9$	$8.5 \times 10^9$
$\kappa$	10560	940	68.0	21.66	12.04	6.88	5.12	4.90	4.45	3.97
$\tan \delta$	2.30	4.43	7.25	2.67	.827	.389	.105	.079	.81	.135

Mass. loams, at 10 MHz, 25°C



Desert sand (Raytheon)

15% R. H. . 25°C. 14 GHz

$\kappa' = 2.88$

$\tan \delta = 0.0115$

Density = 1.633 g/cm<sup>3</sup>

# Miscellaneous Inorganics

## Sands

<u>Sample</u>	<u>Condition</u>		$10^8$	$3 \times 10^8$	$10^9$
Holliston sand	As received $d = 1.54$	$\kappa$	2.73	2.70	2.67
		$\tan \delta$	0.0044	0.00278	0.00217
		% $H_2O$	0.09	0.06	0.06
	Dry $d = 1.54$	$\kappa$	2.70	2.69	2.67
		$\tan \delta$	0.0022	0.00235	0.0017
	1% $H_2O$ $d = 1.53$	$\kappa$	3.25	3.22	3.12
		$\tan \delta$	0.0084	0.059	0.062
	3% $H_2O$ $d = 1.39$	$\kappa$	3.40	3.35	3.30
		$\tan \delta$	0.0224	0.0930	0.120
	10% $H_2O$ $d = 1.45$	$\kappa$	7.25	7.15	6.85
		$\tan \delta$	0.056	0.054	0.056
	93% RH $d = 1.58$	$\kappa$	2.87	2.85	2.81*
		$\tan \delta$	0.006	0.020	0.063*
Slatterville sand No. 60	As received $d = 1.60$		2.84	2.82	2.80
			0.0070	0.0033	0.0033
	Dry $d = 1.60$		2.82	2.80	2.78
			0.0038	0.0024	0.0016
	1% $H_2O$ $d = 1.53$		2.80	2.72	2.67
			0.032	0.040	0.50
	3% $H_2O$ $d = 1.48$		3.60	3.51	3.19
			0.947	0.061	0.089
	10% $H_2O$ $d = 1.54$		7.50	7.35	7.06
			0.090	0.109	0.081
	93% RH $d = 1.60$		2.92	2.90	2.84
			0.004	0.0106	0.0364

\* %  $H_2O$  = 0.385

Miscellaneous Inorganics  
Ices, glacial

Dielectric Constants

Sample, Source	Density (g/cm <sup>3</sup> )	Temp. (°/C)	Frequency in MHz					
			110*	150	300	500	1000	2700
Dartmouth Firm ice No. 12	0.898	-1	3.22	3.21	3.20	3.20	3.20	3.201
		5	3.21	3.20	3.20	3.20	3.20	3.195
		10	3.20	3.19	3.19	3.19	3.19	3.188
		20	3.18	3.18	3.18	3.18	3.18	3.175
		30	3.17	3.16	3.16	3.16	3.16	3.163
		40	3.15	3.15	3.15	3.15	3.15	3.151
		50	3.14	3.14	3.14	3.14	3.14	3.139
		60	3.13	3.13	3.13	3.13	3.13	3.129
Dartmouth Sea ice No. 14	0.917	-1	3.41	3.38	3.34	3.31	3.28	
		5	3.33	3.31	3.29	3.27	3.26	
		10	3.28	3.26	3.25	3.24	3.24	
		15	3.26	3.24	3.24	3.23	3.22	
		20	3.23	3.22	3.21	3.20	3.20	3.197
		25	3.22	3.21	3.20	3.19	3.19	3.184
		30	3.21	3.20	3.19	3.18	3.17	3.173
		40	3.19	3.18	3.17	3.16	3.16	3.159
Tuto Tunnel	0.902	50	3.18	3.17	3.16	3.15	3.15	3.144
		60	3.15	3.15	3.14	3.14	3.14	3.133
		-1	3.22	3.21	3.20	3.20	3.20	3.197
		5	3.20	3.19	3.19	3.19	3.19	3.189
		10	3.19	3.18	3.18	3.18	3.18	3.182
		20	3.17	3.17	3.17	3.17	3.17	3.170
		30	3.16	3.16	3.16	3.16	3.16	3.159
		40	3.15	3.15	3.15	3.15	3.15	3.149
Little America	0.881	50	3.14	3.14	3.14	3.14	3.14	3.138
		60	3.13	3.13	3.13	3.13	3.13	3.129
		-1	3.09	3.08	3.07	3.07	3.07	3.065
		5	3.07	3.06	3.06	3.06	3.06	3.057
		10	3.06	3.05	3.05	3.05	3.05	3.050
		20	3.04	3.04	3.04	3.04	3.04	3.036
Arctic	0.835	30	3.03	3.03	3.03	3.03	3.03	3.025
		40	3.01	3.01	3.01	3.01	3.01	3.012
		50	3.00	3.00	3.00	3.00	3.00	3.000
		-1	2.90					2.880
		5	2.89					2.875
		10	2.88					2.870
		20	2.86					2.861
		30	2.85	2.85	2.85	2.85	2.85	2.852
		40	2.85	2.85	2.85	2.84	2.84	2.844
		50	2.84	2.84	2.84	2.84	2.84	2.835
		60	2.83	2.83	2.83	2.83	2.83	2.827

\* 110 MHz values are extrapolated, not measured.



Ices (cont)

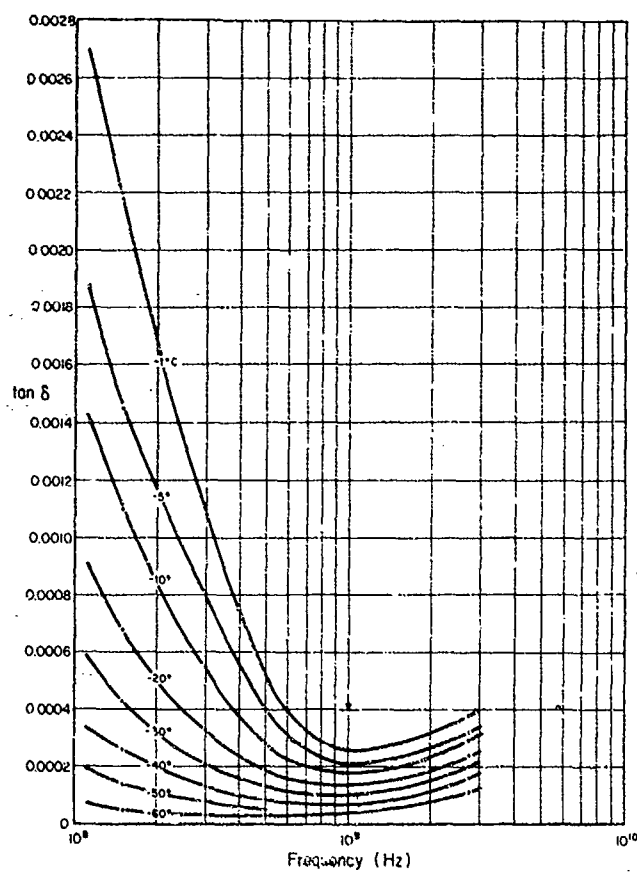
Loss Tangent

Frequency in MHz

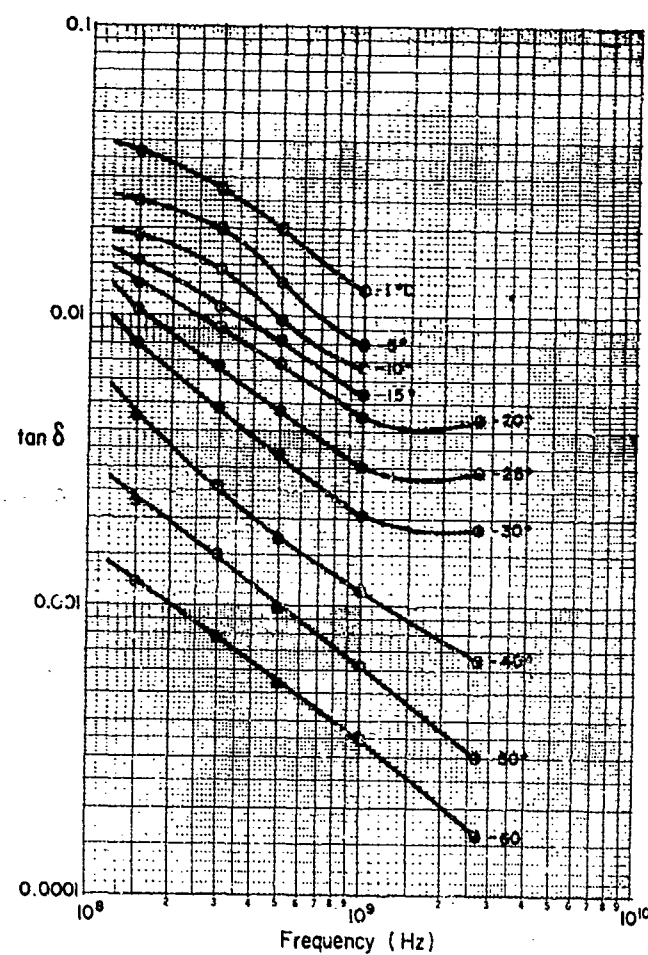
Sample, Source	Temp. (°C)	110 *	150	300	500	1000	2700
Dartmouth No. 12	-1	.0030	.0022	.00108	.00052	.0004	.00038
	5	.0019	.00144	.00076	.00040		.00034
	10	.00145	.00110	.00055	.00028		.00030
	20	.00092	.00068	.00033	.00019		.00024
	30	.00059	.00043	.00021	.00013		.00020
	40	.00034	.00026	.00013	.00008		.00016
	50	.00020	.00014	.00008	.00005		.00014
	60	.00008	.00005	.00003	.00003		.00013
Dartmouth No. 14	-1	.039	.037	.0225	.0200	.0122	
	5	.026	.025	.0200	.0130	.0080	
	10	.0195	.0190	.0145	.0097	.0067	
	15	.017	.0157	.0107	.0082	.0054	
	20	.015	.0130	.0091	.0068	.0045	.0044
	25	.013	.0106	.0067	.0047	.0030	.0029
	30	.010	.0080	.0048	.0033	.00205	.00185
	40	.0058	.0045	.0026	.0017	.00112	.00065
	50	.0028	.0023	.0015	.00098	.00062	.00030
	60	.0014	.0012	.00078	.00054	.00035	.00016
Tuto Tunnel	See data for Dartmouth No. 12 (no measurable difference)						
Little America	-1	.0049	.0037	.0018	.00106	.00054	.00038
	5	.0035	.0026	.0013	.00072	.00037	.00032
	10	.00286	.00217	.00108	.00056	.00025	.00027
	20	.0020	.00154	.00078	.00038	.00018	.00024
	30	.00146	.00116	.00057	.00029	.00014	.00020
	40	.00105	.00085	.00044	.00025	.00013	.00014
	50	.00076	.00057	.00030	.00021	.00012	-
* 110 MHz values are extrapolated, not measured.							
Arctic	-1			-			.00033
	5			-			.00029
	10		Cooling failed, sample melted				.00024
	20			-			.00018
	30			.00045			.00016
	40			.00032			.00014
	50			.00022			.00013
	60			.00015			.00013

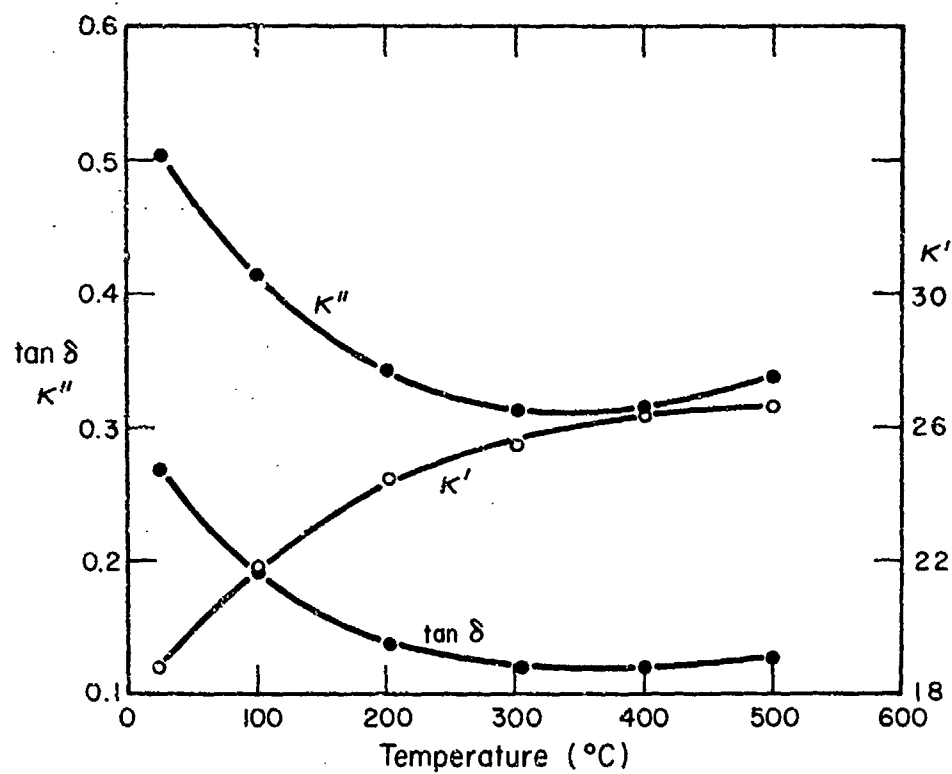
Ices (cont.)

Dartmouth No. 12

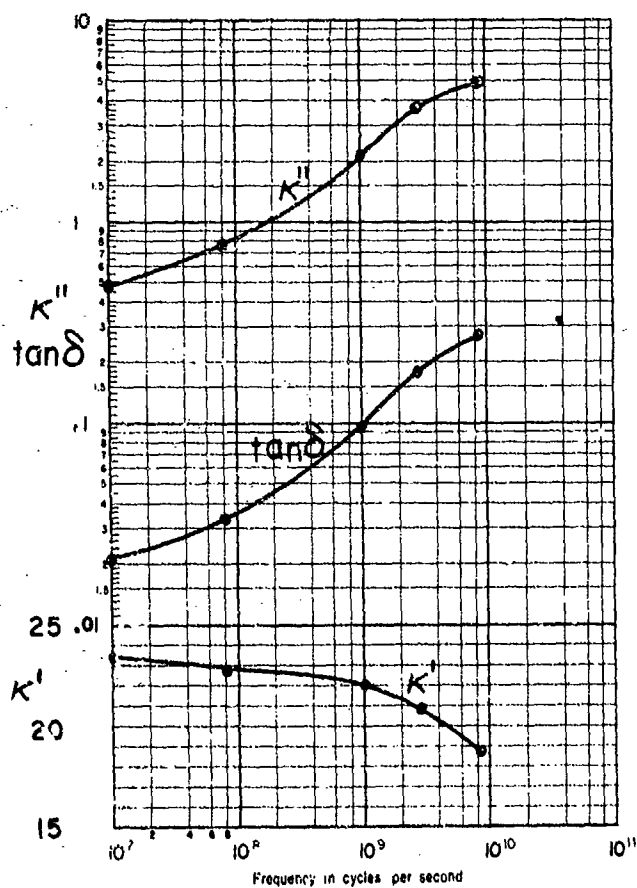


Sea ice





CFI 1006



# Miscellaneous Inorganics (cont.)

Corning Code 0330

3 GHz

$\kappa$

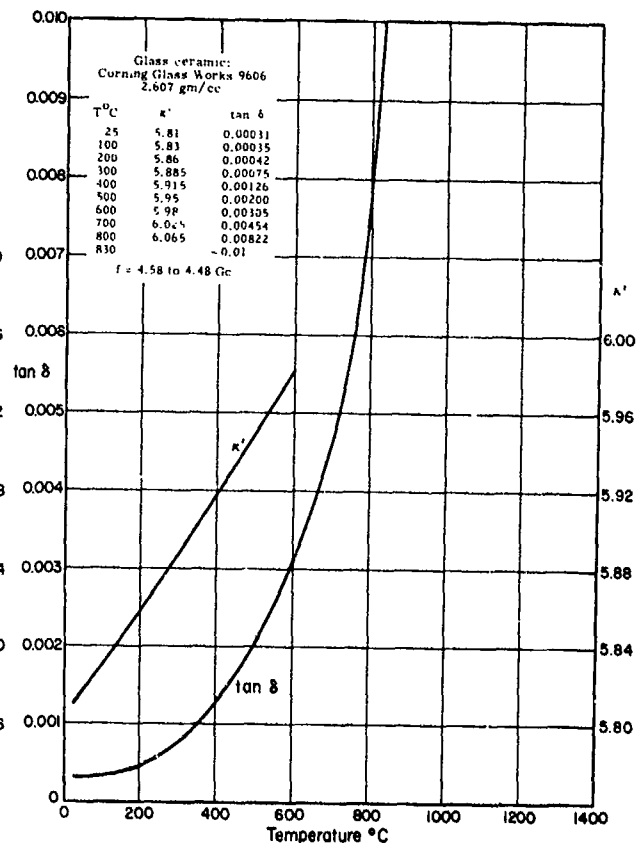
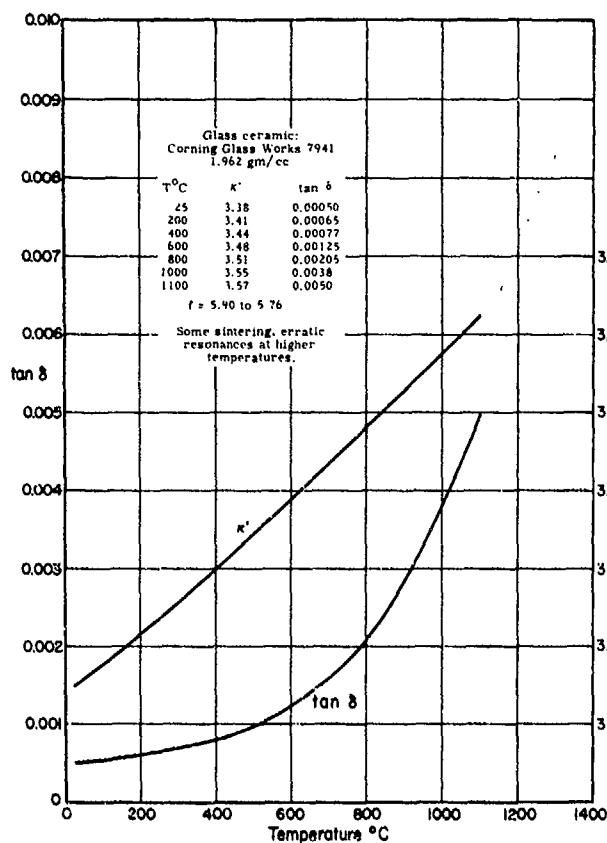
6.58

Corning Glass

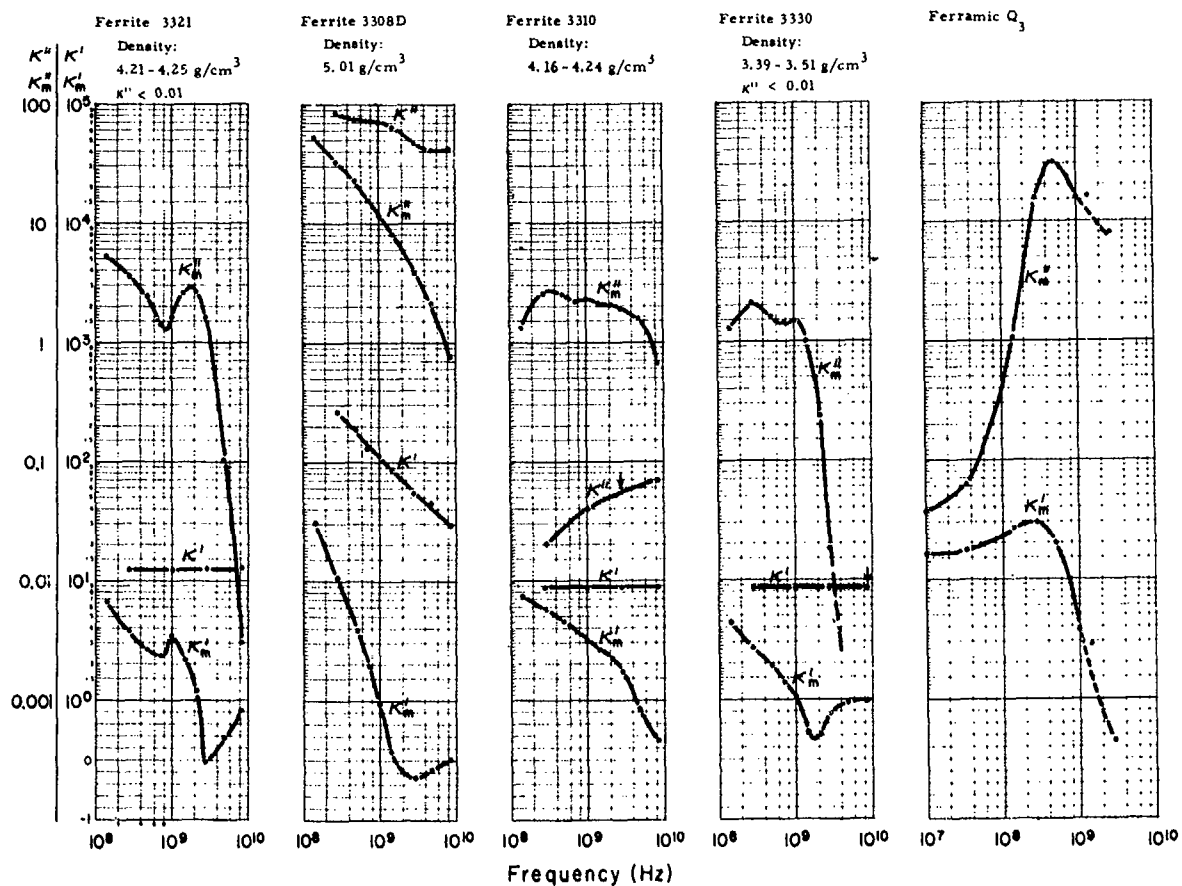
25°C

$\tan \delta$

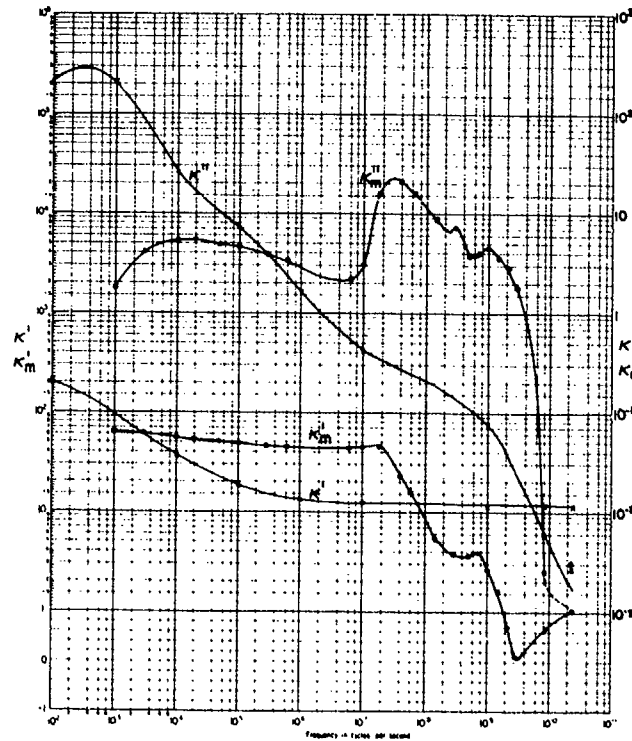
.0055



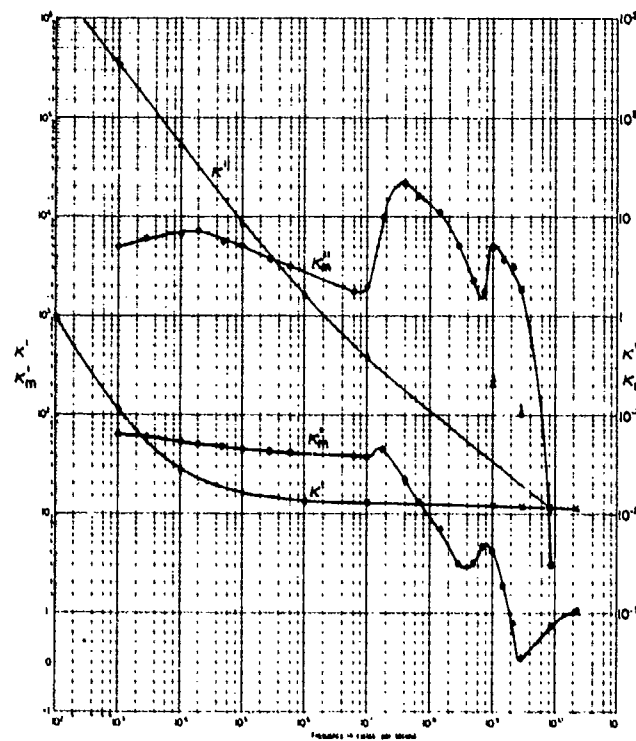
## Ferrites



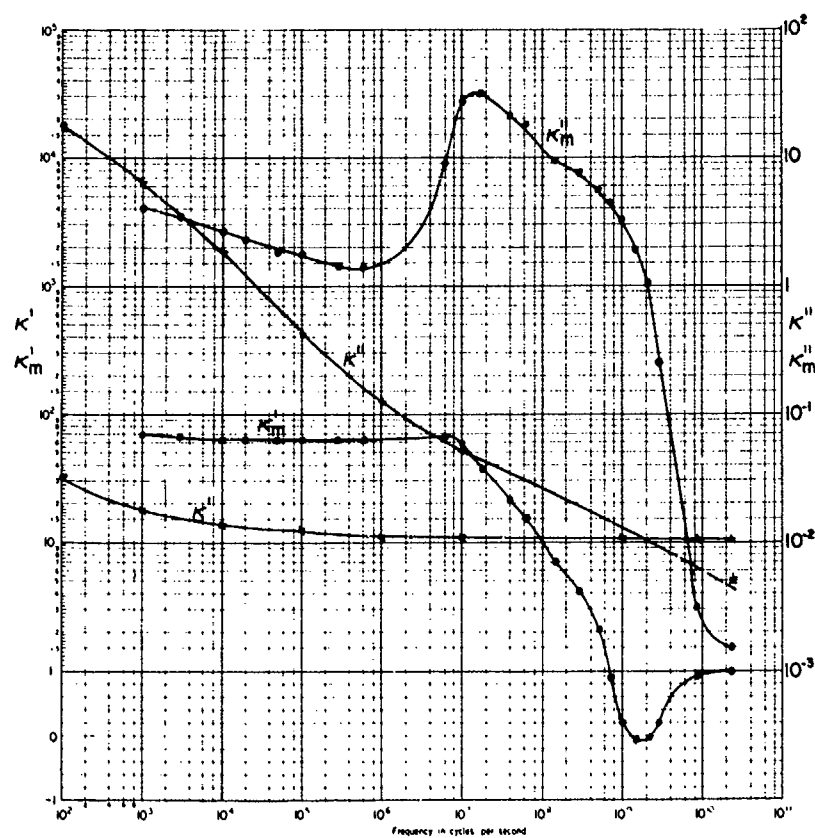
R-1



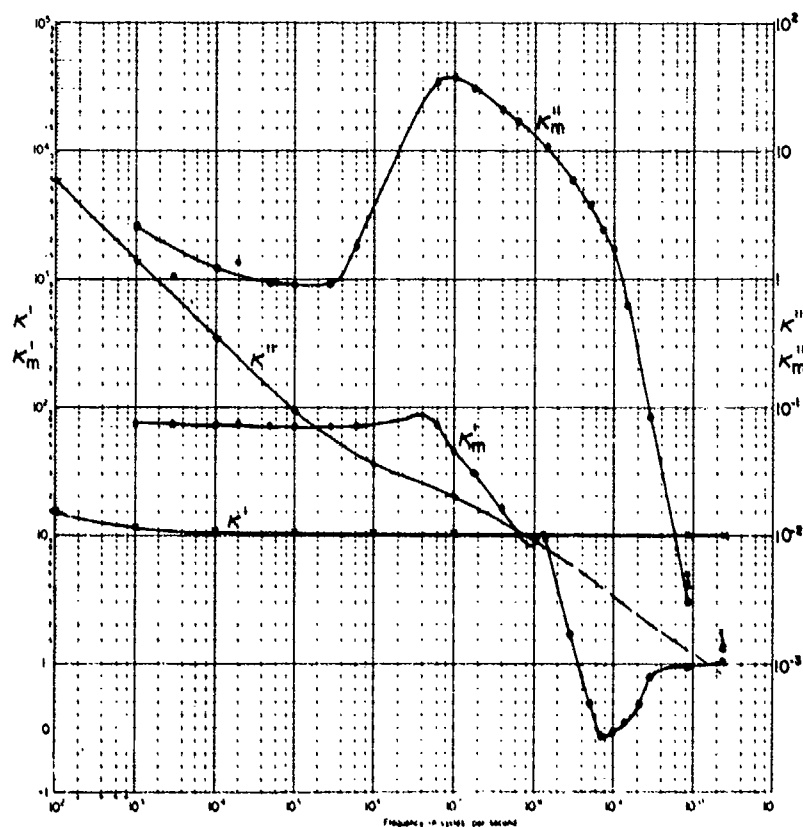
R-4



R-5



R-6



# Miscellaneous Inorganics

Havelex, glass-bonded mica  
At 8.52 GHz, 25°C

Haveg Industries, Inc.  
Taunton Division

Type	$\kappa'$	$\tan \delta$
1080	6.35	.0025
1090	6.17	.0058
1101	8.89	.0027
2101	6.35	.0013
2103	9.2	.0021
2801	6.35	.0020
2803	6.05 -	.00255 -
	6.39	.0026

Isomica 4950

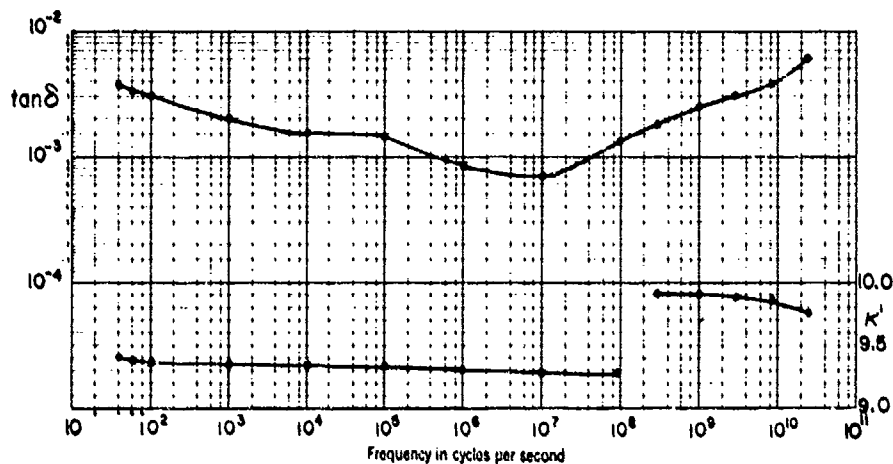
General Electric  
Electronic Components Div.

Vacuum baked for 36 hrs. at 125°C, E || sheet

Freq. (MHz)	$\kappa$	$\tan \delta$
300	5.33	.0013
8520	5.31	.00207
8520	5.32*	.0025*

\* 50% relative humidity.

Mycalex 410

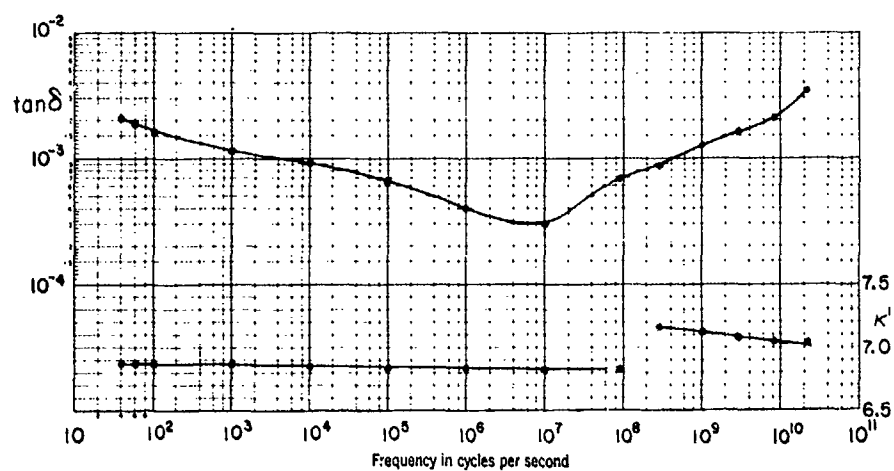


Note: all Mycalex samples from sheet stock.  $10^2$  through  $10^8$  Hz, E  $\perp$  sheet.  
 $3 \times 10^8$  to  $2.4 \times 10^{10}$  Hz, E || sheet.

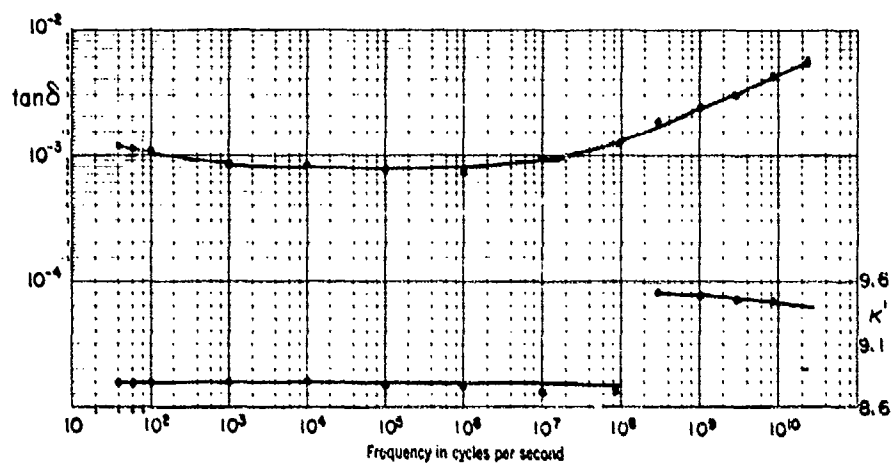


# Mycalex (cont.)

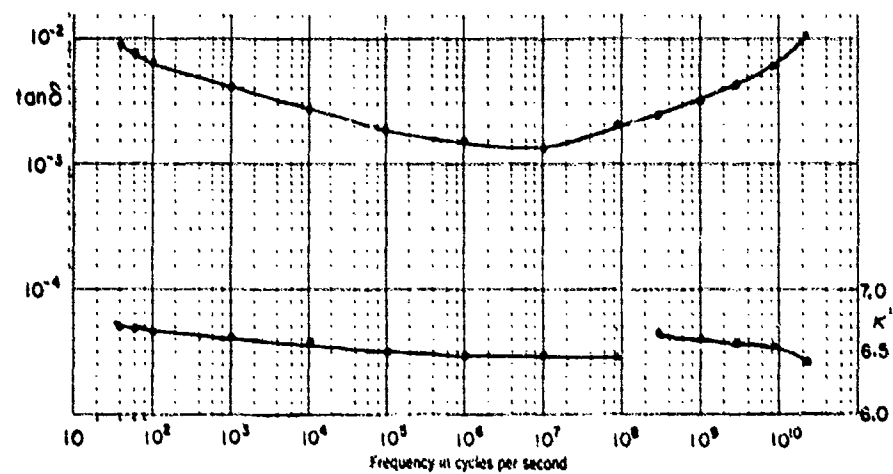
500



555

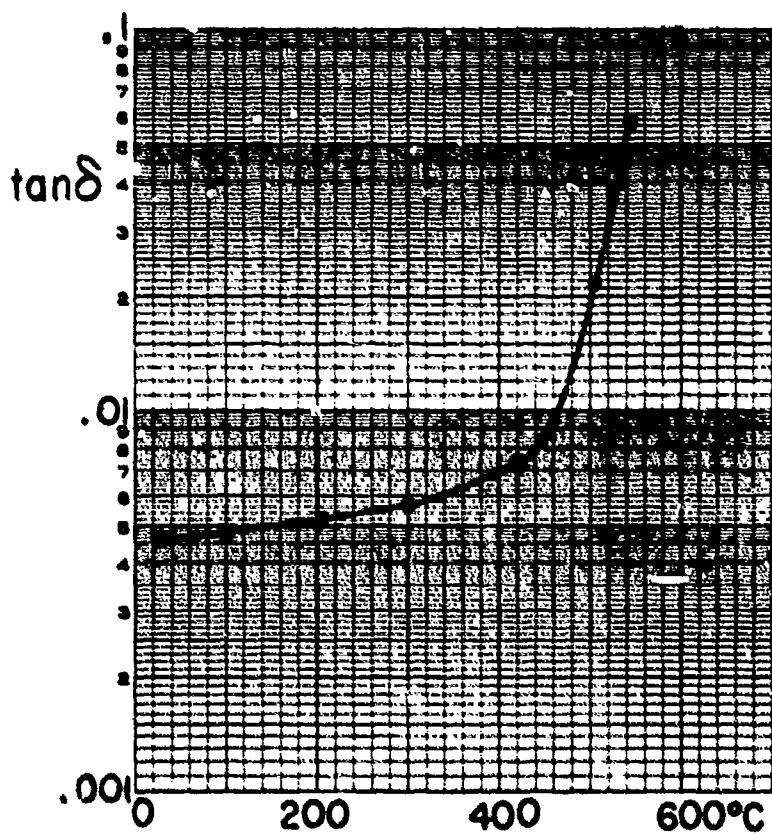
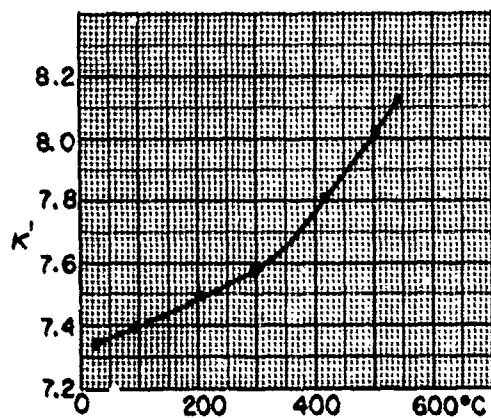
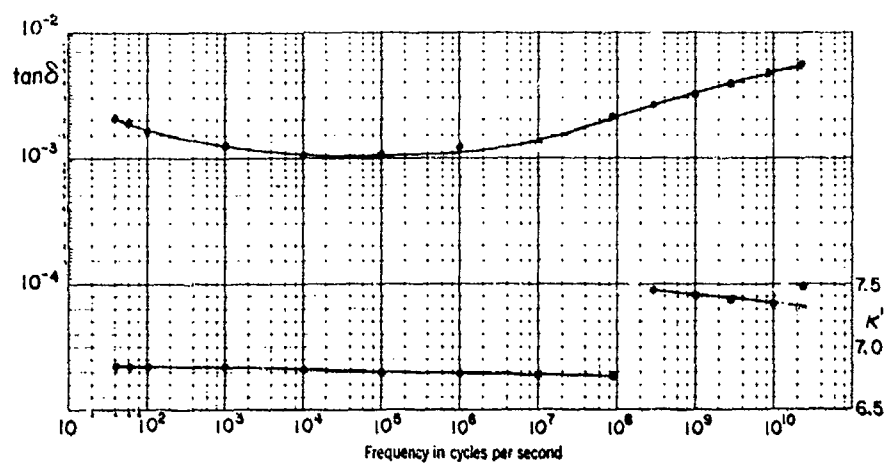


560



Mycalex (cont.)

620



## Asphalt pavement

Sample	Density	(Hz)	$10^5$	$10^6$	$10^7$	$10^8$
S	Dry	$\kappa$	4.51	4.34	4.21	4.14
		$\tan \delta$	.0280	.0221	.0181	.0198
S	Wet	$\kappa$	42.0	17.7	9.03	6.54
		$\tan \delta$	.875	.638	.444	.233
L	Dry	$\kappa$	4.79	4.73	4.70	4.61
		$\tan \delta$	.0187	.0158	.0123	.0121
L	Wet	$\kappa$	14.48	9.28	6.65	6.01
		$\tan \delta$	.368	.280	.190	.104

## Raytheon

Asphalt pavement at 40% R. H., 25°C, 14 GHz

Sample No.	Thickness (cm)	Density (g/cm <sup>3</sup> )	H <sub>2</sub> O (%)	Orientation	$\kappa'$	$\tan \delta$
1	0.1			Independent	4.73	.0114
2	0.1			"	4.62	.0103
3	0.1				5.03	.0120
4	0.1				5.48	.0095
5	0.91	2.35	.754	Face 1	6.02	.021
				Face 1, 90°	5.53	.052
				Face 2	5.37	.204
				Face 2, 90°	5.44	.102

## Liquid asphalt

## Esso

f (Hz)	$\kappa'$	$\tan \delta$
$1 \times 10^9$	2.46	.0017
$3 \times 10^9$	2.46	.0019
$8.5 \times 10^9$	2.46	.0013

Solid asphalt formed by burning liquid for 2 days at 300°C

$1.5 \times 10^6$	2.64	.0043
$10^7$	2.64	.0030
$1.8 \times 10^7$	2.64	.0027
$4 \times 10^7$	2.64	.0025
$8.5 \times 10^9$	2.63	.0018

# Miscellaneous Inorganics

## Concrete pavement

## California Highway Department

Sample	Density	(MHz)	0.1	1	10	100
S1	Dry	$\kappa$	9.05	7.97	7.01	6.57
		$\tan \delta$	.0946	.0913	.0730	.0536
S1	Wet	$\kappa$	176.5	69.2	23.5	13.2
		$\tan \delta$	.822	1.088	.734	.485

## Concrete pavement at 40% R. H. , 25°C, 14 GHz

## Raytheon

1	0.1			Various	5.03-5.06	.026-.029
2	0.1			Various	5.06-5.17	.034-.030
3	0.335	2.14	2.21	Face 1	5.21	.059
				Face 1, 90°	5.20	.0612
				Face 2	5.30	.0509
				Face 2, 90°	5.26	.0505
				Face 1	4.71	.0470
4	0.453	2.04	2.81	Face 1, 90°	4.60	.0455
				Face 2	4.70	.0487
				Face 2, 90°	4.55	.0487

# Miscellaneous Inorganics

## Salt

Raytheon

<u>Sample</u>	<u>Condition</u>		$10^8$	$3 \times 10^8$	$10^9$
Granulated purified salt	As received $d = 1.39$	$\kappa$	3.28	3.27	3.25
		$\tan \delta$	0.0019	0.0018	0.0040
		% $H_2O$	0.05	0.06	.08
	Dry $d = 1.39$	$\kappa$	3.25	3.25	3.23
		$\tan \delta$	0.0009	.0006	0.0012
Fine flake salt	As received $d = 0.960$	$\kappa$	2.72	2.67	2.63
		$\tan \delta$	0.026	0.037	0.025
		% $H_2O$	0.28	0.36	0.40
	Dry $d = 0.956$	$\kappa$	2.64	2.63	2.62
		$\tan \delta$	0.0017	0.0014	0.0031

John Manville Service Boards at 25°C The Sippican Corporation

	Style 61 - 1/4"			Style 71 - 1/8"	
MHz	$\kappa$	$\tan \delta$		$\kappa$	$\tan \delta$
0.05	12.78	0.429		5.18	0.342
1	6.43	0.347		3.46	0.150
60	3.87	0.091		3.07	0.017
300*	4.20	0.188		3.54	0.043
1000*	3.98	0.137		3.50	0.024
0.05*	149.	0.733		61.8	0.625
1*	46.3	0.740		15.8	1.09

\* Electric field in plane of sheet, others E sheet.

### III. ORGANIC COMPOUNDS

(Listed according to manufacturer or source)

Artificial concrete

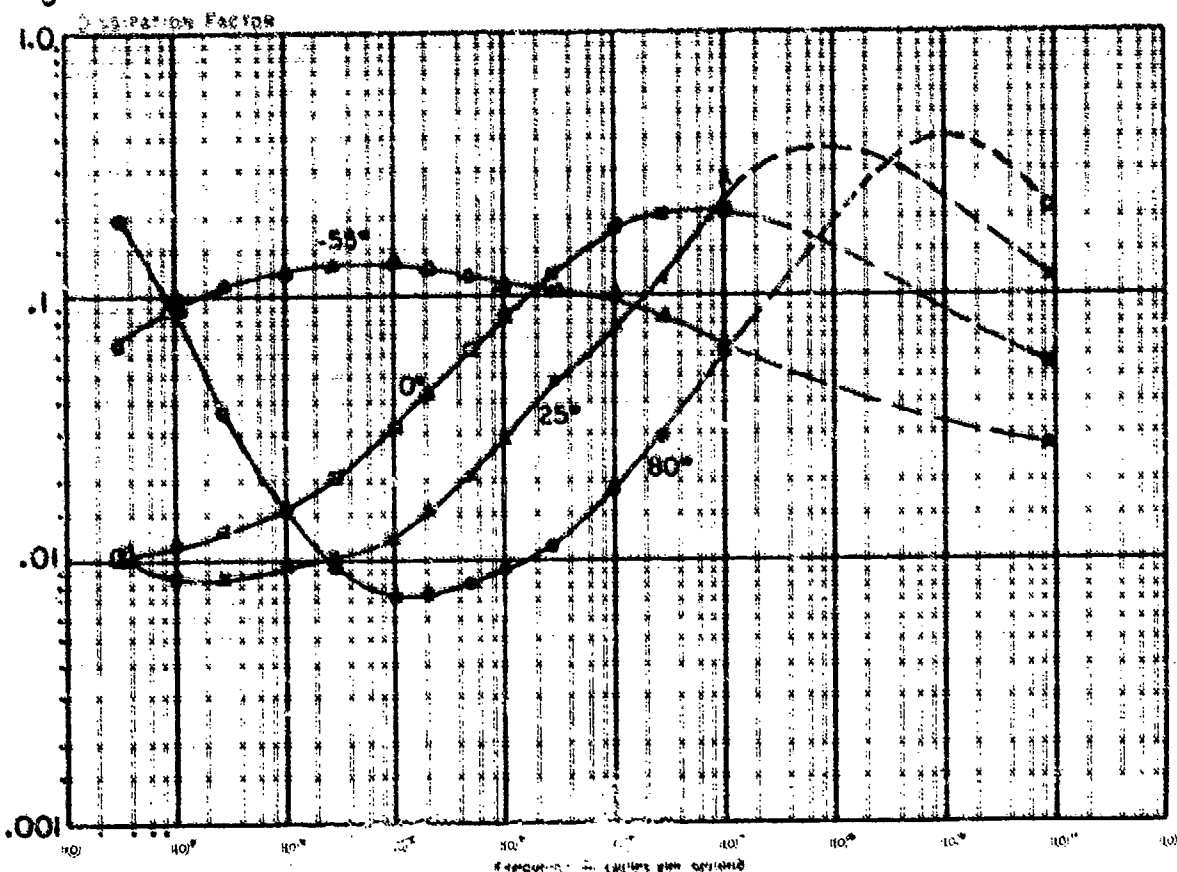
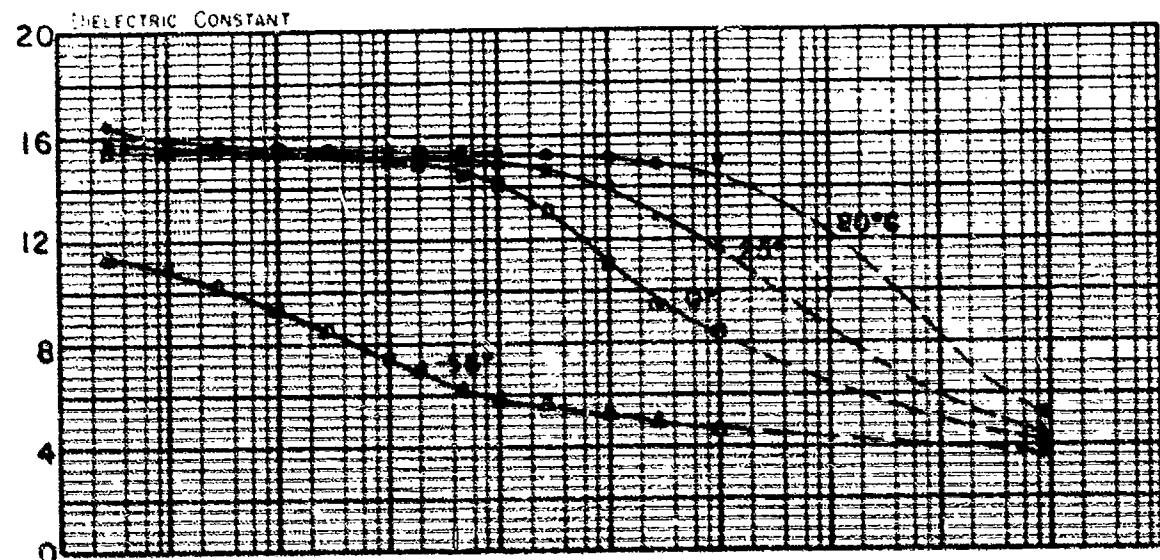
American Concrete Products

Material measured to be isotropic in  $\kappa$  within 0.5%

Freq. (MHz)	150	300	1000	3000
$\kappa$	6.06	6.04	6.02	6.0
$\tan \delta$	0.0107	0.0134	0.0125	0.0123

Cyanoethylated cotton moulding

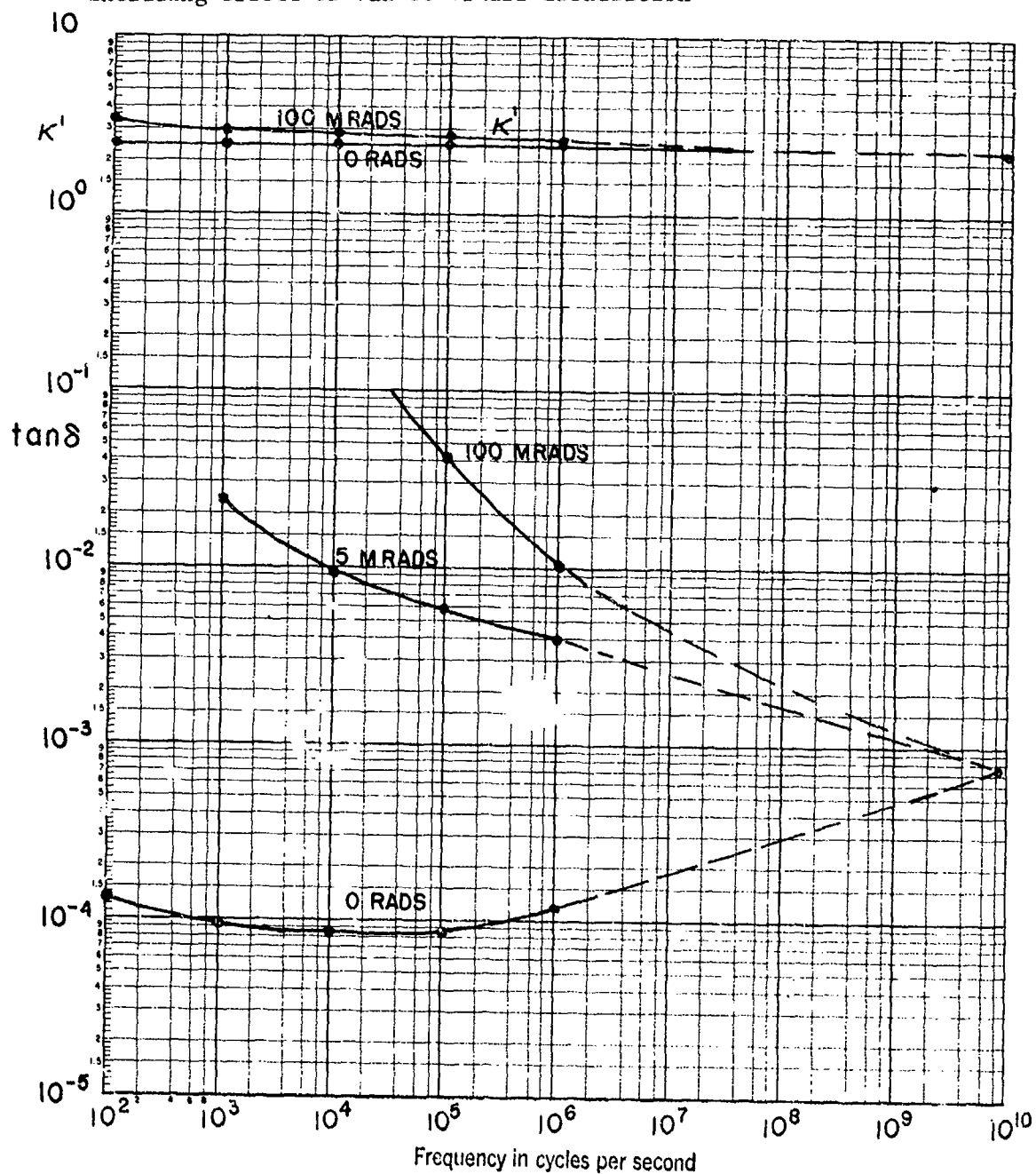
American Cyanamid



Cymac 325,

American Cyanamid

including effect of van De Graaff irradiation



Conformal coating 1517-36-3  
25°C, 50% relative humidity

Amicon Corporation

Freq. (Hz)	K	$\tan \delta$
$10^2$	4.31	0.0206
$10^3$	4.21	0.0204
$10^6$	3.76	0.0298

Volume resistivity  $3.7 \times 10^{13}$  ohm-cm

Surface resistivity  $>6 \times 10^{14}$  ohms per square

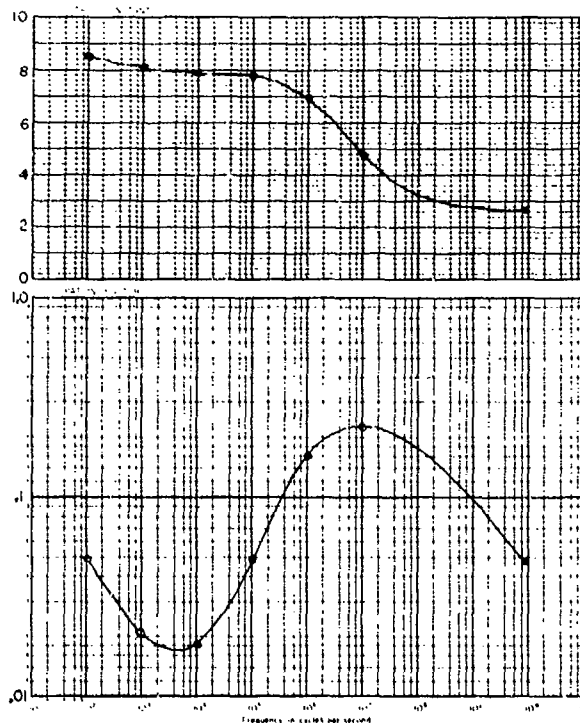
Polyethylene, irradiated  
At 25°C

Source: Amphenol Corp.

Freq. (Hz)	$\kappa'$	$\tan \delta$
$10^3$	$2.28 \pm .02$	$.59 \pm .05$
$10^6$		$.82 \pm .05$
$10^8$		$2.3 \pm .3$
$4 \times 10^8$	$2.27 \pm .02$	$2.9 \pm .5$
$10^9$		$2.8 \pm .3$
$3 \times 10^9$		$2.6 \pm .3$
$8.5 \times 10^9$	$2.260 \pm .01$	$2.5 \pm .2$

Polyvinylidene fluoride

AVCO Research





## Polypropylene

Avisun Corporation  
Post Road  
Markus Hook, Pa. 19061

Freq., Hz	T°C	Natural		Plateable 12-270A	
		$\kappa$	$10^4 \tan \delta$	$\kappa$	$10^4 \tan \delta$
$10^2$	25	2.26	1.50	2.41	15.2
$2 \times 10^2$			1.30		
$4 \times 10^2$			1.18		
$10^3$			1.36	2.41	11.8
$3 \times 10^3$			1.50		
$10^2$			1.65	2.39	10.5
$2 \times 10^4$			1.68		
$5 \times 10^4$			1.66		
$10^5$		2.25	1.51	2.38	8.70
$10^6$		2.25	0.96	2.37	7.25
$10^7$		2.25	1.26	2.36	6.55
$10^8$		2.25	2.04	2.36	8.2
$3 \times 10^8$		2.25	2.8	2.35	12.4
$10^9$		2.25	4.7	2.35	17.5
$3 \times 10^9$		2.25	4.0	2.35	15.7
$5 \times 10^9$	25	2.245	3.7	2.344	12.1
	-55	2.265	3.0	2.352	6.0
	-75	2.271	2.7		
	-195	2.308	$0.7 \pm 0.3$	2.375	2.8
$8.5 \times 10^9$	25	2.245	3.6	2.343	12.3

Polypropylene (cont.)  
Natural, at 8.52 GHz

Avisun Corporation

Sample	Density (g/cm <sup>3</sup> )	T°C	$\kappa$	$\tan \delta$
1 stacked sheet pcs		25	2.246	.00033
2 stacked injection molded pcs		25	2.236	.00035
3 rod	.9073	25	2.245	.00037

Polypropylene, plateable  
12-270A, at 8.52 GHz

Avisun Corporation

Sample	Density	T°C	$\kappa$	$\tan \delta$
4 stacked injection molded pcs	.9500	25	2.442	.00145
5 rod	.9303	25	2.343	.00123

Polytetrafluoroethylene, fiberglass laminate

The Budd Company  
Polychemicals Division

		All values of $\tan \delta$ multiplied by $10^4$										
T°C	Freq. (Hz)	10	$10^2$	$10^3$	$10^4$	$10^5$	$10^6$	$10^7$	$5.5 \times 10^7$	$9 \times 10^7$	$3.14 \times 10^9$	*
25	$\kappa$	2.739	2.740	2.738	2.737	2.735	2.734	2.733	2.732	2.731	2.712	
	1 $\tan \delta$	8.6	7.0	6.7	6.1	6.3	6.95	7.7	10.0	11.7	22.5	
100	$\kappa$		2.710	2.705	2.704	2.698	2.696	2.683			2.680	
	1 $\tan \delta$		11.1	8.10	8.25	7.17	7.07	7.7			31	
250	$\kappa$		2.554	2.534	2.522	2.503	2.502	2.49				
	1 $\tan \delta$		79.0	36.3	20.35	14.9	11.6	10.6				
-78	$\kappa$		2.796	2.793	2.790	2.784	2.78	2.78			2.752	
	1 $\tan \delta$		4.2	5.9	6.8	7.1	7.7	9.8			17	
-195	$\kappa$	2.801	2.799	2.794	2.792	2.787					2.758	
	1 $\tan \delta$	.0005	2.2	4.5	5.1	5.4					12	
-269	$\kappa$	2.789	2.789	2.784	2.783	2.780						
	1 $\tan \delta$	.0003	1.2	2.0	2.2	2.1						

\* Copper cavity

E // sheet

T°C	Freq. (Hz)	$3 \times 10^8$	$10^9$	$3 \times 10^9$	$8.5 \times 10^9$	$1.4 \times 10^{10}$	$2.4 \times 10^{10}$
25	$\kappa$	3.155	3.153	3.152	3.146	3.133	3.127
	$\tan \delta$	28	30	33	40	48	52
100	$\kappa$				3.11		
	$\tan \delta$				39		
250	$\kappa$				3.03		
	$\tan \delta$				36		
-54	$\kappa$				3.17	3.13	
	$\tan \delta$				35	39	
-195	$\kappa$				3.22	3.12	
	$\tan \delta$				28	31	

## Copper-clad laminate PE1153

The Budd Co., Polychem Division

E $\perp$			$10^2$	$10^3$	$10^4$	$10^5$	$10^6$	$10^7$
3-terminal, liquid im- mersion, unclad *	25	$\kappa$			2.420			
		$\tan \delta$						
Declad †	25	$\kappa$			2.451			
		$\tan \delta$						
3-terminal, clad	26	$\kappa$	2.650	2.465	2.438	2.432		
		$\tan \delta$	.0945	.0279	.00484	.00093		
	-195	$\kappa$	2.416	2.415	2.414	2.411		
		$\tan \delta$	.00030	.00033	.00036	.00022		
	-54	$\kappa$	2.433	2.421	2.417	2.413		
		$\tan \delta$	.00042	.00050	.00052	.00031		
2-terminal, clad, meas. 12-21-70	25	$\kappa$	2.495	2.475	2.471	2.469	2.468	2.468
		$\tan \delta$	.01816	.00307	.00083	.00050	.00055	.00035
3-terminal, clad, 2nd sample	25	$\kappa$	2.843	2.504	2.457	2.449		
		$\tan \delta$	.141	.0491	.00811	.00126		
	96	$\kappa$	2.486	2.398	2.389	2.384		
		$\tan \delta$	.0708	.01343	.00230	.00050		
	250	$\kappa$	2.257	2.240	2.232	2.222		
		$\tan \delta$	.0263	.00568	.00238	.00111		
	25	$\kappa$	2.759	2.510	2.459	2.451		
		$\tan \delta$	.0970	.0390	.00748	.00115		
	-54	$\kappa$	2.484	2.484	2.484	2.479	2.464	2.456
		$\tan \delta$	.00034	.00044	.00065	.00062	.00059	.00110
	-195	$\kappa$	2.490	2.487	2.485	2.484	2.482	2.470
		$\tan \delta$	.00029	.00038	.00053	.00028	.00049	.00091
2-terminal, clad	25	$\kappa$				2.462	-	2.458
		$\tan \delta$				.00050	-	.00033
	96	$\kappa$	2.474	2.464	2.461	2.460	2.458	2.455
		$\tan \delta$	.01193	.00226	.00084	.00059	.00058	.00068
	250	$\kappa$	2.333	2.319	2.312	2.309	2.298	2.295
		$\tan \delta$	.01013	.00340	.00177	.00147	.00097	.00070
	25	$\kappa$	2.422	2.415				
		$\tan \delta$	.00995	.00189				
E $\parallel$								
2-terminal, unclad	25	$\kappa$	2.434	2.533	2.431	2.428	2.416	2.413
		$\tan \delta$	.0037	.00094	.00061	.00035	.00052	.0005

\* Refers to sheet stock received without copper.

† Refers to a sample made by mechanically stripping the copper-clad sheet.

Resonant-Cavity Measurements:

~ 8.5 GHz, sample constrained in parallel direction, allowed to expand with temperature against a force 30 lb/sq in the perpendicular direction. Unclad stock.

T °C	E $\perp$		E $\parallel$		Thickness cm
	$\kappa$	$\tan \delta$	$\kappa$	$\tan \delta$	
-194	2.466	.00063	2.420	.00095	1.911
-54	2.437	.00070	2.397	.00104	1.917
23	2.421	.00091	2.383	.00130	1.924
96	2.396	.00117	2.367	.00147	1.948
250	2.296	.0022	2.246	.00185	2.093

Standing-wave method, 25°C

E $\parallel$ , one piece unclad	2.387	.00128
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EKONOL (polyester resin)

The Carborundum Company

Sample 1

Frequency, Hz	T°C	κ	tan δ
10 <sup>2</sup>	25	3.216	.00289
10 <sup>3</sup>	↓	3.210	.00316
10 <sup>4</sup>		3.185	.00336
10 <sup>5</sup>		3.168	.00348
10 <sup>6</sup>		3.156	.00325
10 <sup>7</sup>		3.148	.00220
10 <sup>8</sup>		3.140	.00215
8.5x10 <sup>9</sup>	↓	3.120	.00281
↓	99	3.11	.0030
	155	3.08	.0040
	207	3.07	.0061
	284	3.04	.0104
	350	3.03	.0230
	420	3.03	.0230
	217	2.99	.0067
	25	2.96	.0025

Sample 2

T°C	Freq., Hz	10 <sup>2</sup>	10 <sup>3</sup>	10 <sup>4</sup>	10 <sup>5</sup>	10 <sup>6</sup>	10 <sup>7</sup>
25	κ	2.958	2.954	2.942	2.939	2.923	2.891
	tan	0.00136	0.00201	0.00251	0.00325	0.00337	0.0021
100	κ	2.982	2.962	2.955	2.945	2.926	2.898
	tan	0.00367	0.00263	0.00262	0.00303	0.00391	0.0040
180	κ	3.252	3.182	3.130	3.077	3.031	2.993
	tan	0.0444	0.0160	0.0120	0.0108	0.0099	0.0096
250	κ	4.606	3.415	3.244	3.177	3.096	3.050
	tan	0.767	0.188	0.0368	0.0151	0.0131	0.0138
325	κ	23.57	5.646	3.574	3.267	3.190	3.140
	tan	1.52	1.194	0.316	0.0567	0.0161	0.0127

Polytetrafluoroethylene film

Zitex

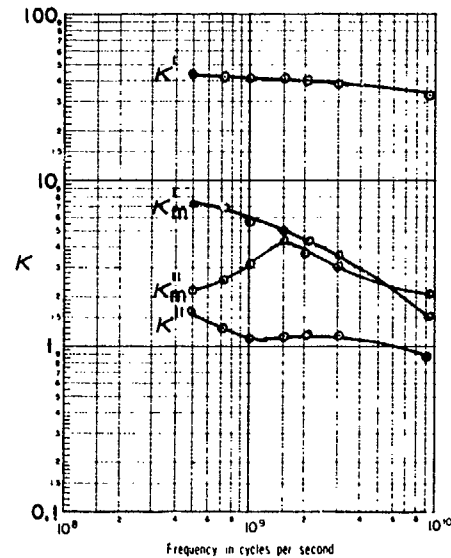
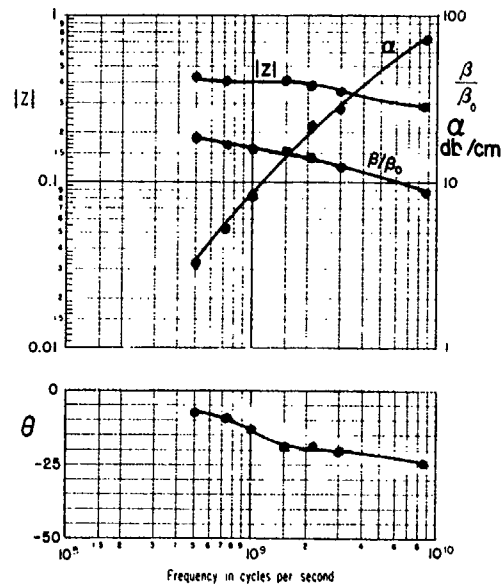
Density 0.463 g/cm<sup>3</sup>

25°C, 8.52 GHz: κ = 1.194, tan δ = .00010

Chemplast Inc.

150 Dey Road

Wayne, N.J. 07470



## Custom Materials

Custom load 4101

Freq. (GHz)	T°C	$\kappa$	$\tan \delta_e$	$\mu'/\mu_0$	$\tan \delta_m$
3	25	13.8	.050	2.69	.451
8.5	25	13.3	.031	1.65	.747
8.5	-67	13.7	.006	1.57	.748
8.5	85	14.5	.051	1.68	.735

Custom 707-4

25°C, 8.52 GHz:  $\kappa = 4.04$ ,  $\tan \delta = .00090$ 

Custom 707-(3.75)

25°C, 8.52 GHz:  $\kappa = 3.753$ ,  $\tan \delta = .00076$ 

## Custom Materials Inc.

FLUORGLAS E 650/2-1200

TFE-fiberglass laminate

Dodge Industries, Inc.

Freq., GHz	T°C	$\kappa$	E $\perp$		E $\parallel$	
			$\tan \delta$	$\kappa$	$\tan \delta$	$\kappa$
8.5	23	2.505	.0014	2.847	.0036	2.847
4	-195	2.533	.00082	2.896	.00172	2.896

## Moulding compound 306

T°C	1 GHz		3 GHz	
	$\kappa'$	$\tan \delta$	$\kappa'$	$\tan \delta$
25	3.92	.00538	3.87	.00622
76	3.91	.0052	3.86	.0058
103	3.90	.0052	3.85	.0058
129	3.89	.0051	3.84	.0056
150	3.87	.0050	3.83	.0055
216	3.83	.0050	3.78	.0051
255	3.80	.0052	3.75	.0051
305	3.77	.0056	3.72	.0054
410	3.68	.0064	3.63	.0068
504	3.62	.0058	3.58	.0066
301	3.75	.0048		

## Dow Corning

T°C	8.52 GHz	
	$\kappa'$	$\tan \delta$
-55	3.85	.0060
25	3.84	.0067
61	3.835	.00655
118	3.825	.0064
147	3.82	.00635
199	3.807	.00625
315	3.74	.00615
400	3.66	.0061
499	3.57	.0060
296	3.72	.0061

## Silastic RTV 501

T°C	1000 MHz	3000 MHz	8500 MHz
-55	$\kappa'$ 3.17	3.07	
	$\tan \delta$ 0.025	0.037	
23	$\kappa'$ 2.89	2.88	2.87
	$\tan \delta$ 0.0053	0.0104	0.0175
150	$\kappa'$ 2.62	2.62	
	$\tan \delta$ 0.042	0.0045	
RTV 521	23	$\kappa'$ 3.33	3.31
		$\tan \delta$ 0.0086	0.0257
RTV 1602	-55	$\kappa'$ 3.09	3.03
		$\tan \delta$ 0.0220	0.0308
	23	$\kappa'$ 2.93	2.92
		$\tan \delta$ 0.0073	0.0117
	150	$\kappa'$ 2.77	2.75
		$\tan \delta$ 0.0044	0.0060
RTV 5350	-55	$\kappa'$ 3.22	3.14
		$\tan \delta$ 0.0234	0.0287
	23	$\kappa'$ 3.06	3.05
		$\tan \delta$ 0.0043	0.0088
	150	$\kappa'$ 2.82	2.79
		$\tan \delta$ 0.0040	0.0043
S-6538	-55	$\kappa'$ 3.01	2.96
		$\tan \delta$ 0.0242	0.0260
	23	$\kappa'$ 2.99	2.98
		$\tan \delta$ 0.0069	0.0124
	150	$\kappa'$ 2.78	2.77
		$\tan \delta$ 0.0039	0.0047
Sylgard 182	-55	$\kappa'$ 2.90	2.86
		$\tan \delta$ 0.0200	0.024
	23	$\kappa'$ 2.79	2.77
		$\tan \delta$ 0.0081	0.0120
	150	$\kappa'$ 2.50	2.48
		$\tan \delta$ 0.0026	0.0040

## Sylgard 182, at 1 MHz

T°C	$\kappa$	$\tan \delta$
25	2.86	.00132
70	2.72	.00080
25 again	-	.00109
25 (after 24 hrs. in H <sub>2</sub> O) wt. gain 0.019%	2.86	.00142

## Dow Corning

## Sylgard 184, at 25°C

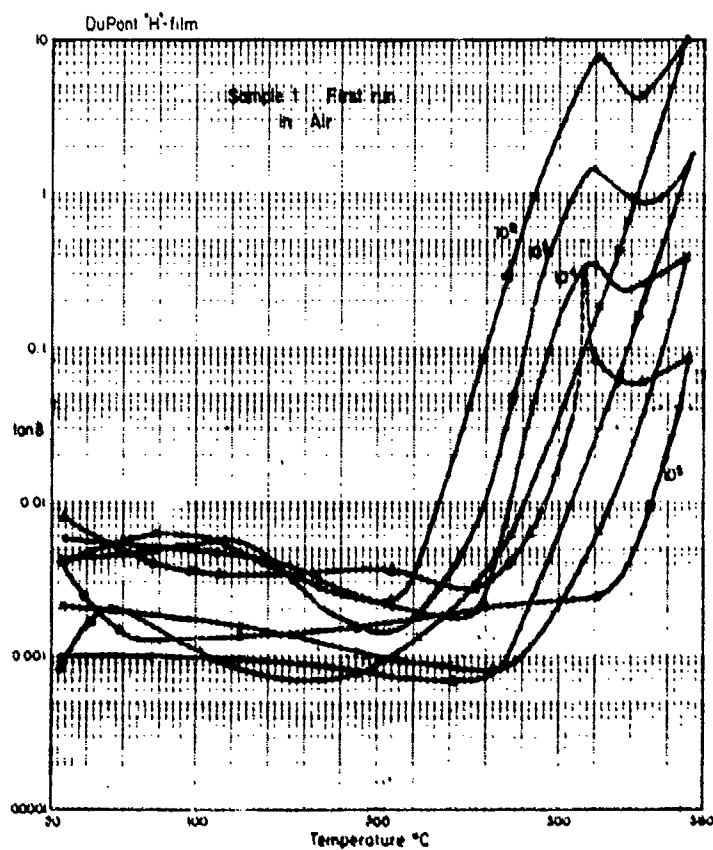
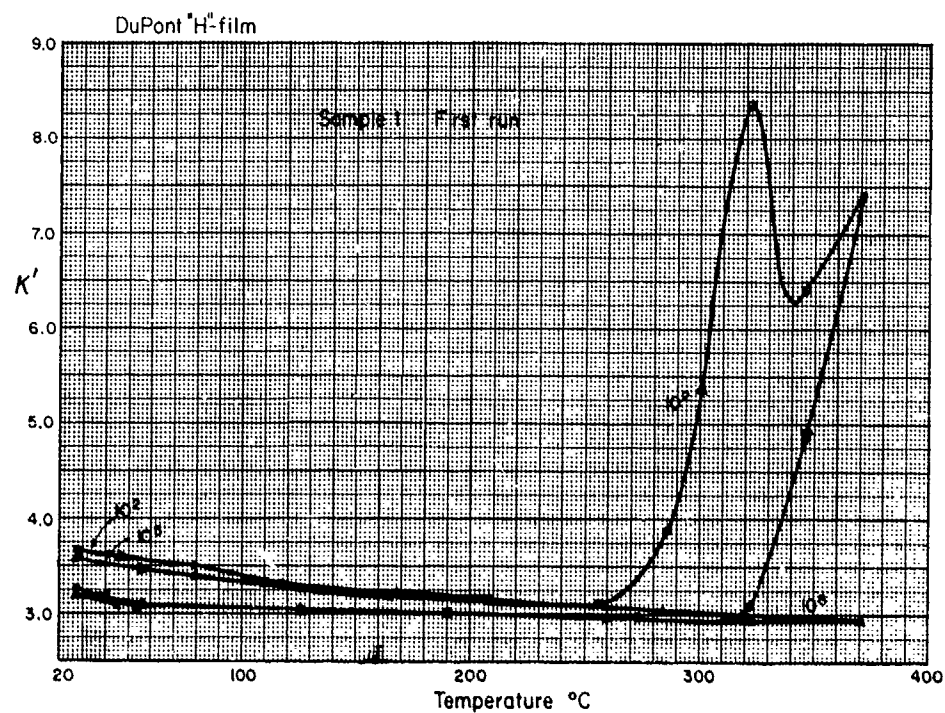
Freq. (Hz)	50	10 <sup>3</sup>	10 <sup>5</sup>	10 <sup>6</sup>
$\kappa$	2.86	2.86	2.84	2.84
10 <sup>4</sup> $\tan \delta$	2	10.2	18.4	14.0

## Sylgard 184 (2nd sample at 1 MHz)

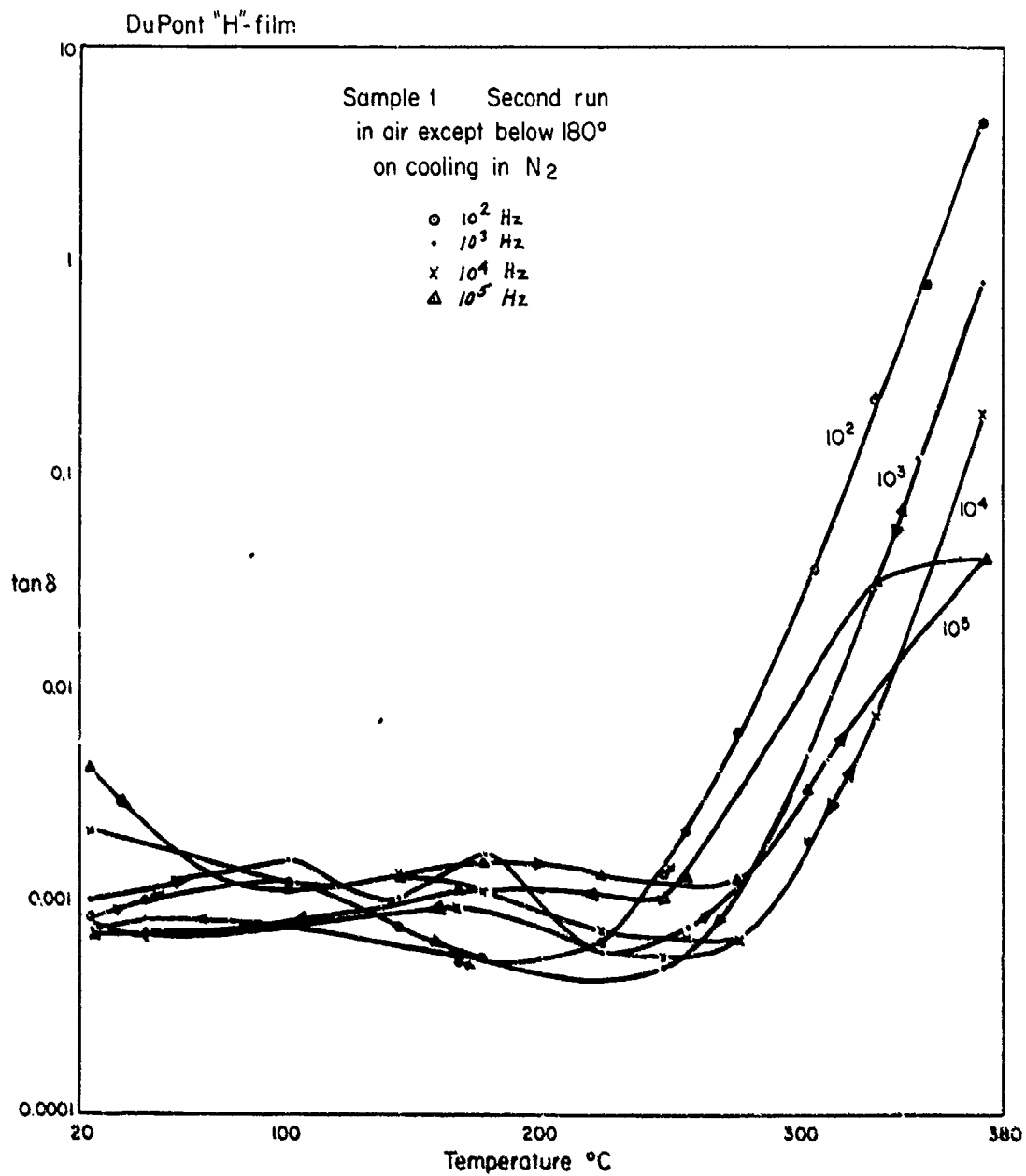
T°C	$\kappa'$	$\tan \delta$
25	2.88	.00123
70	2.70	.00071
25	-	.00040
25 (after 24 hrs. in H <sub>2</sub> O) wt. gain 0.0252%	2.89	.00129

## DC-92,007

8.52 GHz, 25°C, 50% R.H.,  $\kappa' = 4.92$ ;  $\tan \delta = 0.091$

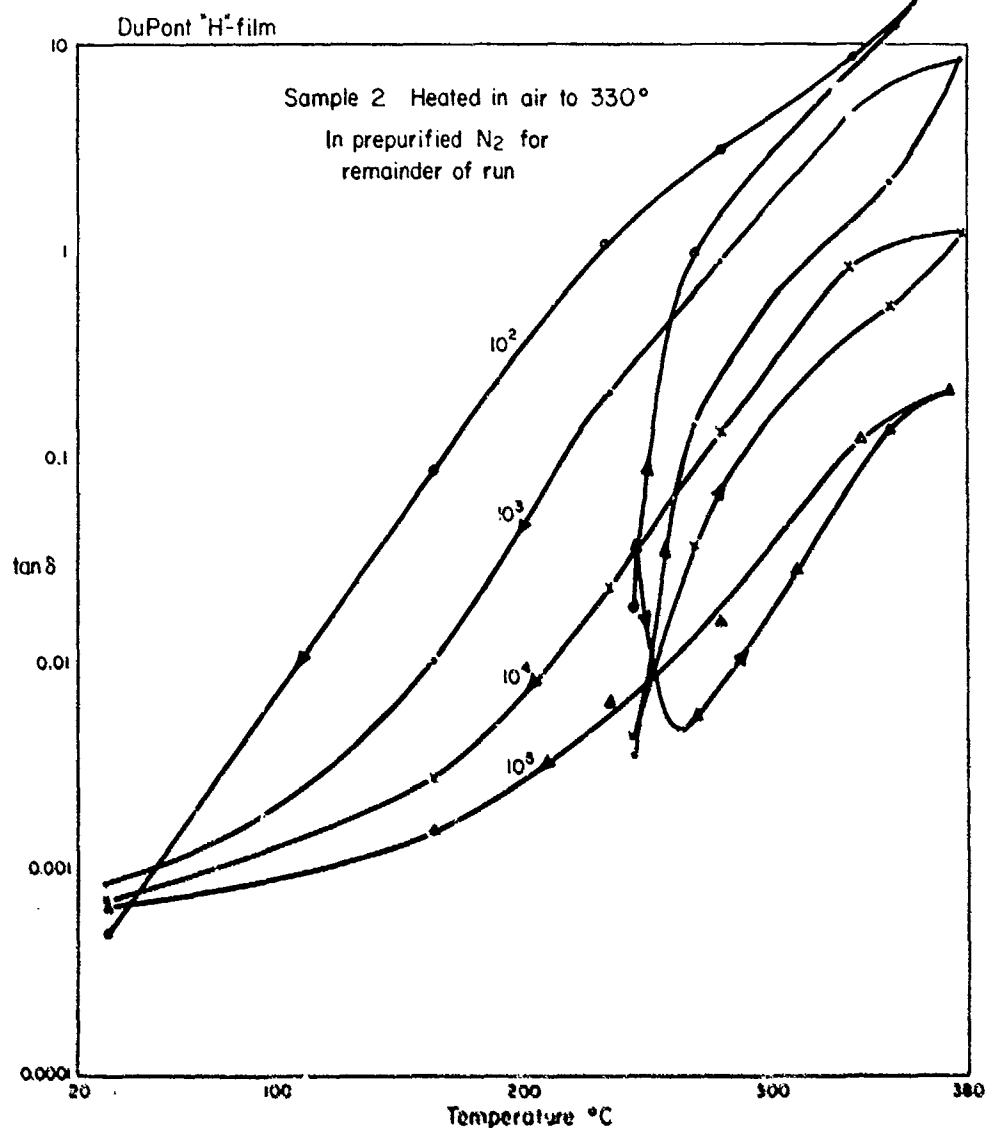






"H"-film (cont.)

E. I. Dupont de Nemours and Co.



"Kapton"

E. I. Dupont de Nemours and Co.

Type 500 H film, at 25°C, 45% relative humidity

Electric field in plane of sheet,  $\kappa \pm 0.05$ ,  $\tan \delta \pm 0.0005$

After 48 hrs. at 100°C

Freq. (GHz)	$\kappa$	$\tan \delta$	$\kappa$	$\tan \delta$
0.3	3.43	.0074	-	-
1	3.40	.0076	3.30	.0041
3	3.37	.0080	3.28	.0044
8.5	3.33	.0087	3.26	.0047
24	3.25	.0098	-	-

After 12 to 18 hrs. vacuum bake at 425°C, 2 microns, 8.52 GHz:

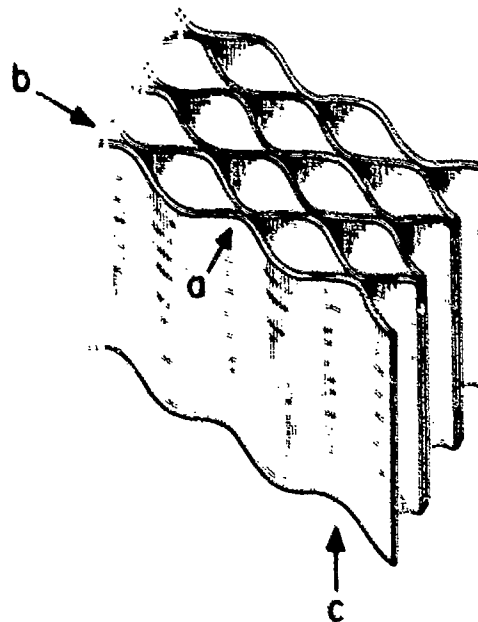
$\kappa = 3.03 \pm 0.1$ ,  $\tan \delta = .0015 \pm .0003$

Nonex honeycombs  
At 8.52 GHz

E. I. du Pont de Nemours and Company

Sample No.	Density	<u>a direction</u>		<u>b direction</u>		<u>c direction</u>	
		E $\perp$ double-layer seam		E $\parallel$ double-layer seam		E $\parallel$ holes	
		$\kappa$	$\tan \delta$	$\kappa$	$\tan \delta$	$\kappa$	$\tan \delta$
1	1.398	1.0348	.00089	1.0441	.00141	1.0855	.00212
2	2.892	1.0519	.00165	1.0669	.00229	1.0951	.00350
3	3.938	1.0788	.00176	1.1258	.00326	1.1444	.0041
4	4.039	1.0808	.00187	1.1020	.00278	1.1265	.0049
5	4.124	1.0827	.00274	1.1045	.00359	1.1351	.0046
6	4.259	1.0863	.00197	1.1340	.00382	1.1270	.0045
7	4.701	1.0928	.00315	1.1115	.00297	1.1455	.0047
8	5.603	1.0990	.00205	1.1781	.00468	1.1869	.0065
8*	5.603	1.1010	.00330	1.1667	.00628		

\* At 100°C, all other values at 25°C

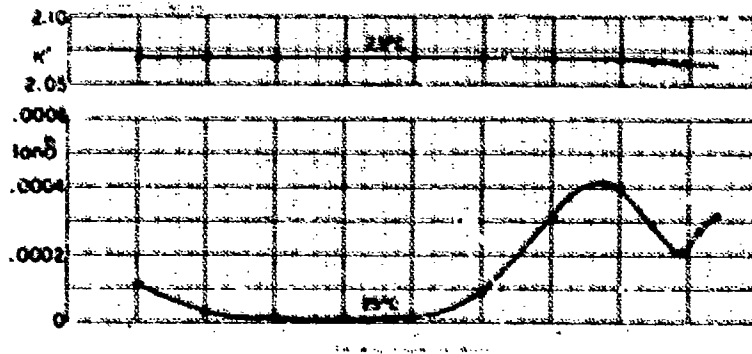
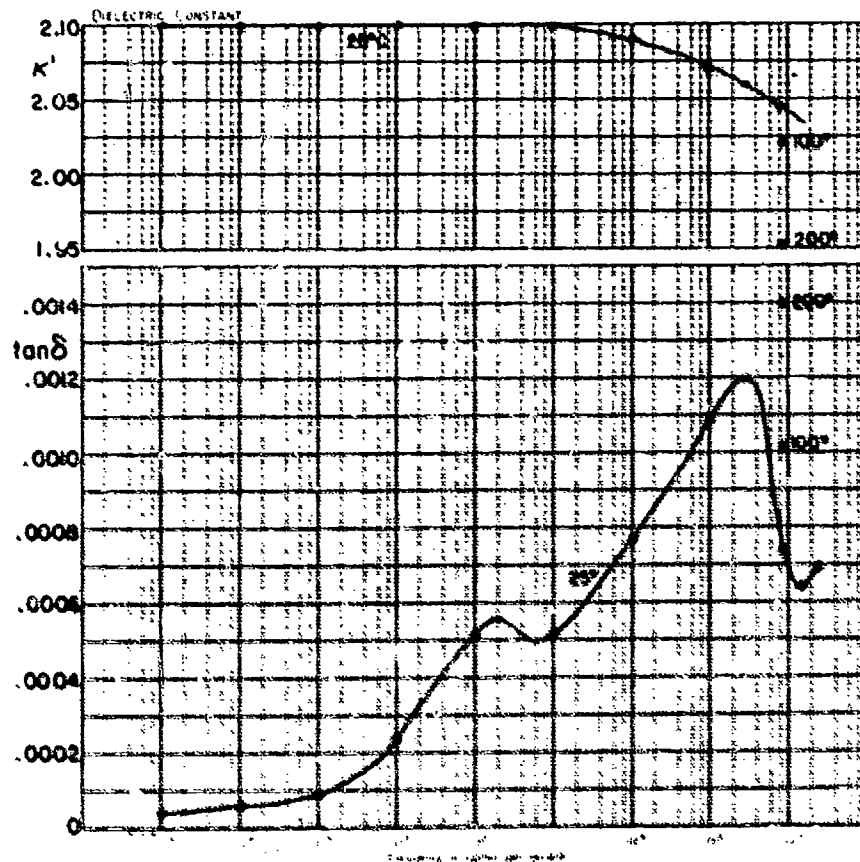


Teflon FEP (1963)

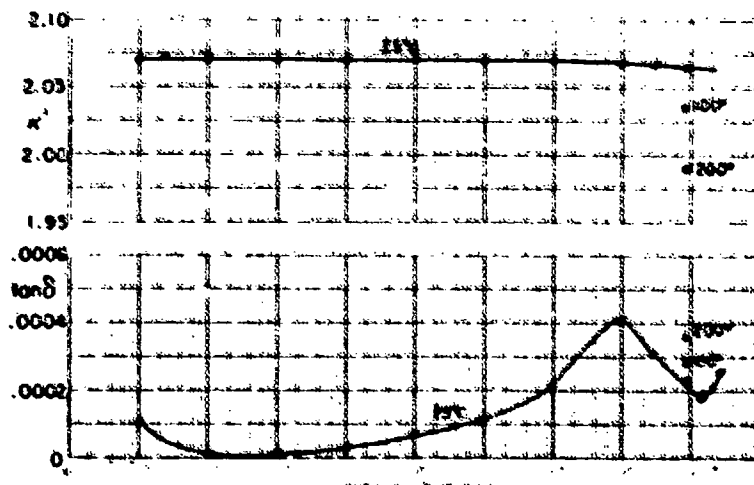
E. I. DuPont de Nemours and Co.

Density = 2.153 g/cm<sup>3</sup>, at 25°C, 8.52 GHz  
 $\kappa' = 2.058$ ,  $\tan \delta = 0.00108$

Teflon FEP (1964)



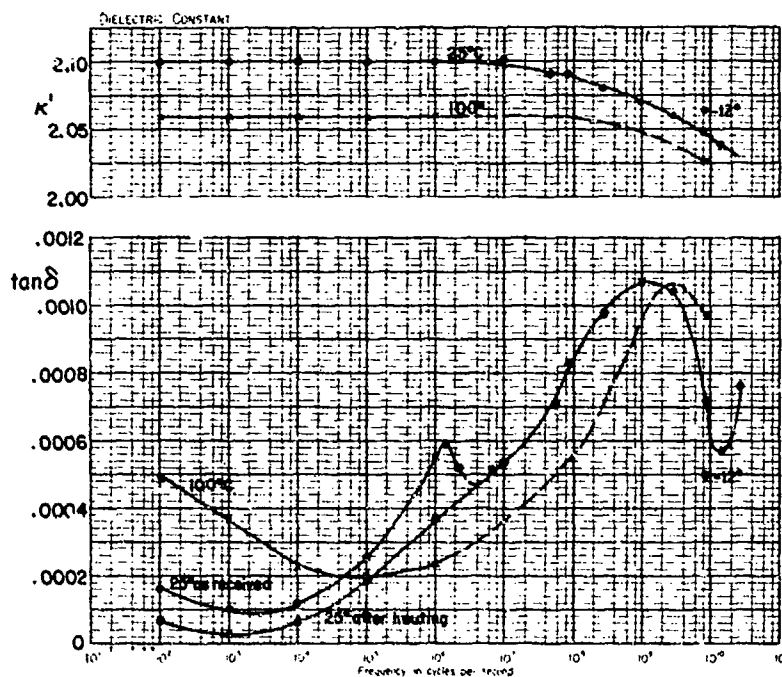
TFE-7 (1964)



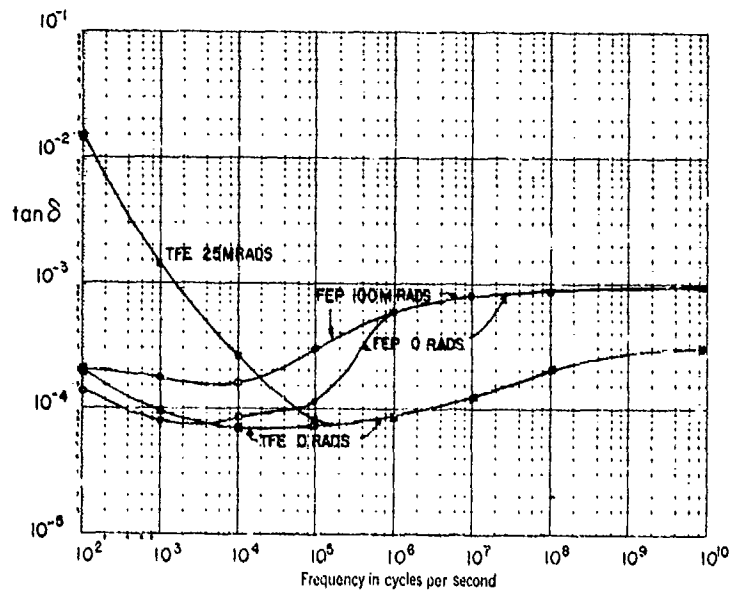
TFE-6C (1964)

Teflon T-100, \*) Lot 38180  
Density at 25°C = 2.152 g/cm<sup>3</sup>

E. I. Dupont de Nemours and Co.



Teflon 100X (FEP) 1960 and TFE  
Effect of Van De Graaff irradiation, 25°C



\*) Electric data also apply to:

Teflon 9033, Lot 10601, density at 25°C = 2.147 g/cm<sup>3</sup>

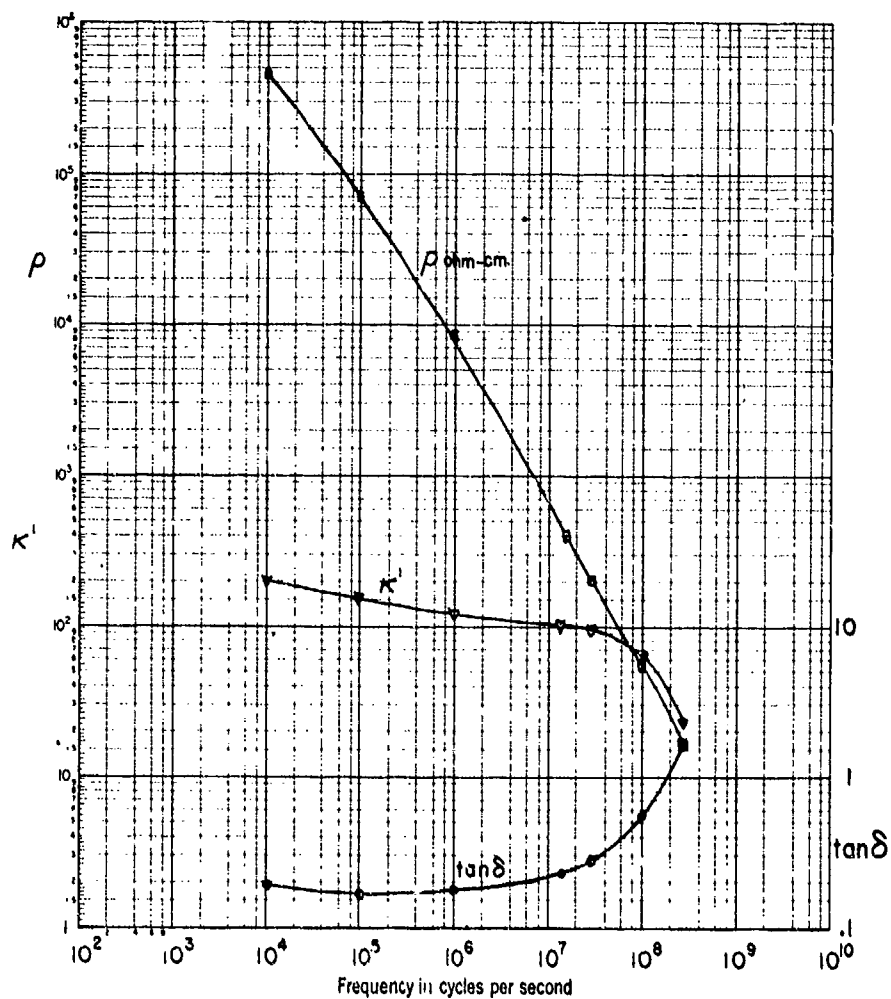
"Polyguide"

Electronized Chemicals Corp.

		3 GHz		8.52 GHz		% wt. increase
		$\kappa'$	$\tan \delta$	$\kappa'$	$\tan \delta$	
As received	25°C	2.32	.00034	2.319	.00030	
	-48°C			2.320	.00017	
	74°C			2.300	.00040	
After 24 hrs. H <sub>2</sub> O		2.32	.00047	2.320	.00038	.007

Emerson and Cumming A-19

graphite fiber loaded plastic, November 1966



"Eccogel" 1265

Emerson & Cuming

T <sup>o</sup> C	Freq. (Hz)		10 <sup>3</sup>		10 <sup>6</sup>	
	K	tan δ	K	tan δ	K	tan δ
25	7.60	.025	7.20	.0595	4.05	.1115
70					6.02	.0545
25 again					-	.0897
25 (after 24 hrs. in H <sub>2</sub> O) wt. gain 1.08%					5.38	.128

"Eccofoam FH"

Emerson & Cuming

3.938 lb/cu.ft.

8.52 GHz		24 GHz	
K	tan δ	K	tan δ
1.0856	.00161	1.0798	.00165

RTV-11

General Electric  
Silicone Products Dept.

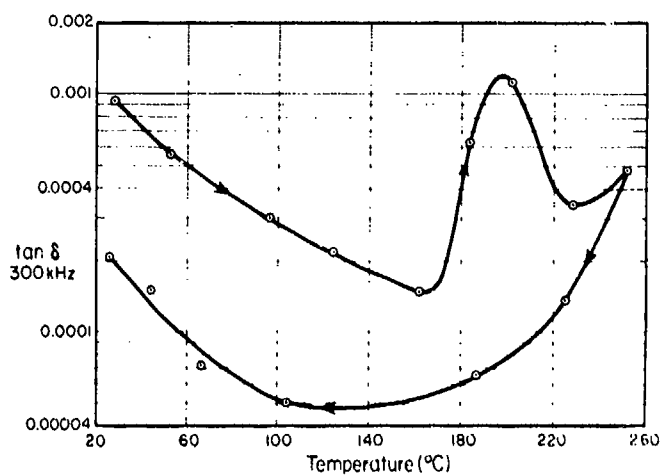
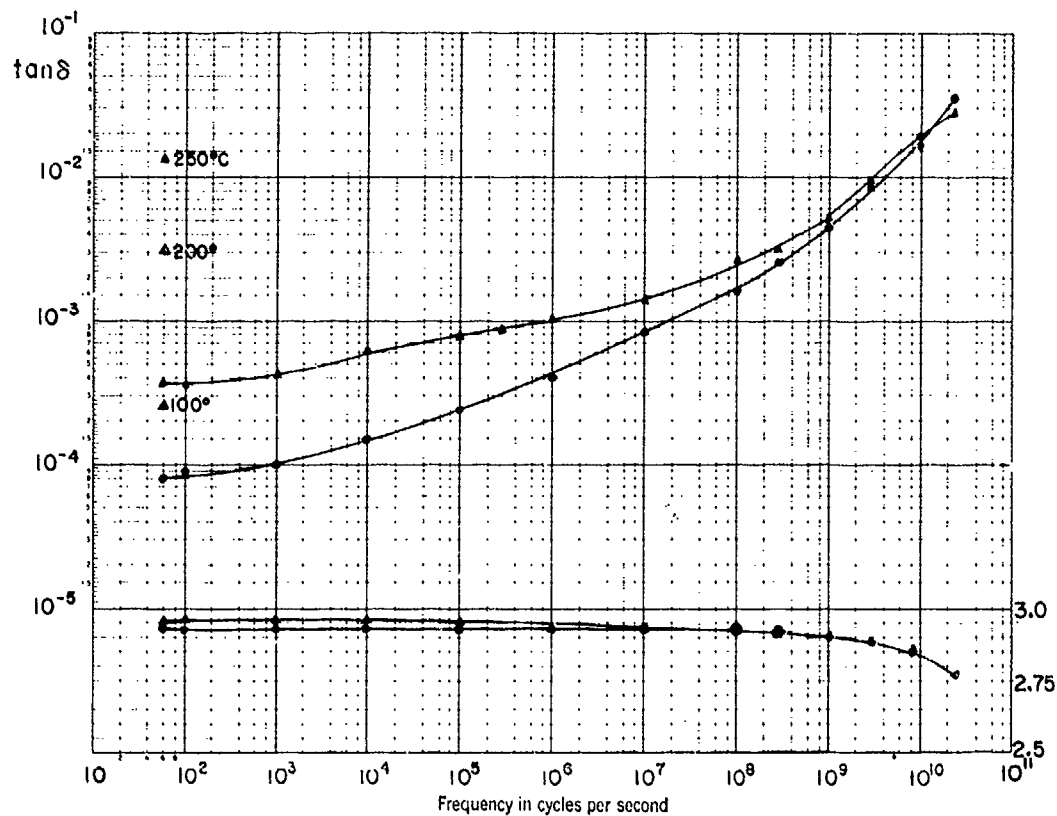
At 1 MHz

T <sup>o</sup> C	K	tan δ
25	3.25	.00285
70	3.05	.00372
25	-	.00242
25 (after 24 hrs in H <sub>2</sub> O) wt. gain .035%	3.31	.00543

## SE900 Silicone Rubber

General Electric

Δ Sample cured 1 hr at 300°F, measured at 50% R. H.  
 ○ Normal cure



Lexan	General Electric	
f(Hz)	$\kappa'$	tan $\delta$
$8.5 \times 10^9$	2.77	.00615
$2.5 \times 10^{10}$	2.75	.00593



"3M" board

3-M

		3 GHz		8.52 GHz		% wt. increase
		$\kappa'$	$\tan \delta$	$\kappa'$	$\tan \delta$	
As received	25°C	2.32	.00038	2.316	.00037	
	-48°C			2.316	.00015	
	74°C			2.300	.00040	
After 24 hrs H <sub>2</sub> O	25°C	2.32	.00060	2.316	.00043	

Scotchcast 221

3-M

At 1 MHz

T°C	$\kappa$	$\tan \delta$
25	3.06	.0273
70	3.73	.1373
25	-	.0245
25 (after 24 hrs. in H <sub>2</sub> O) wt. gain .274%	3.12	.0352

Polyimide foams

Monsanto

At 8.52 GHz

	Density (lbs/cu.ft.)	T°C	$\kappa$	$\tan \delta$
HD-139	8.4	25	1.1439	.00277
		150	1.128	.00040
		304	1.118	.00045
		25	1.126	.0014
HD-140	16.7	25	1.301	.00507
		154	1.264	.00094
		307	1.260	.00121
		25	1.260	.00037
HD-144	21.8	25	1.412	.00635
		148	1.355	.00135
		303	1.382	.00190
		28	1.351	.0068

Polyurethane rigid foam, at 399 MHz

Nopco Chemical Corp.

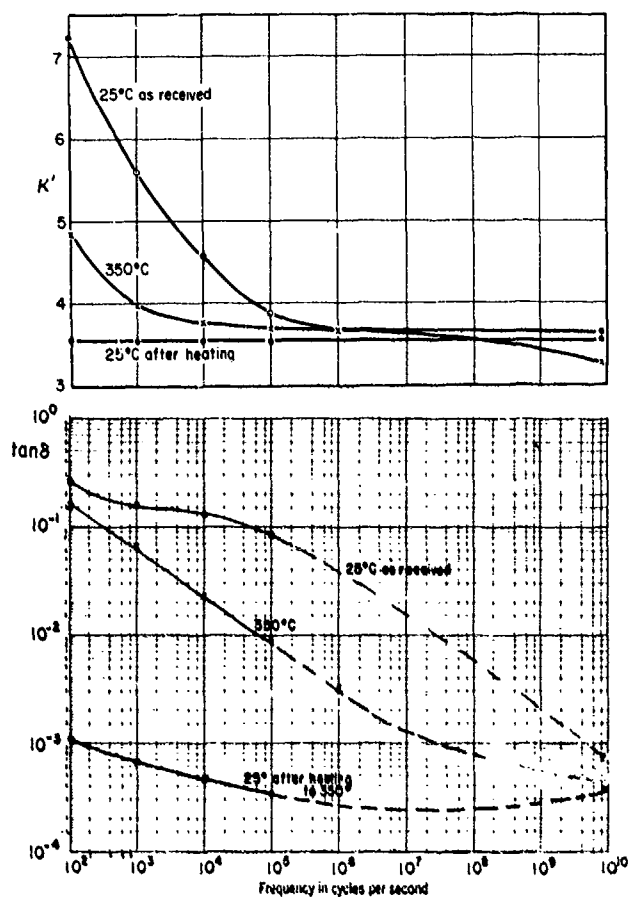
3.80 lbs/cu. ft

7.54 lbs/cu. ft

T <sup>°</sup> F	K'	tan $\delta$	K'	tan $\delta$
77	1.087	.00136	1.165	.00242
116	1.088	.00176	1.170	.00276
164	1.093	.00208	1.175	.00344

Fluorosint (1960)

Polymer Corp.



Radar tape

At 14.2 GHz

Quantum Inc.  
Lufbery Ave.  
Wallingford, Conn.

T°C	$\kappa$	$\tan \delta$
25	3.56	.0132
150	3.37	.0055
320	3.32	.0074
477	3.36	.0130

Plastics

Raytheon Company

Resin - "Bakelite" epoxy (Union Carbide)  
- CY-178 epoxy (Ciba Products)  
Hardener - hexahydrothalic Anhydride, HHPA (Allied Chem.)

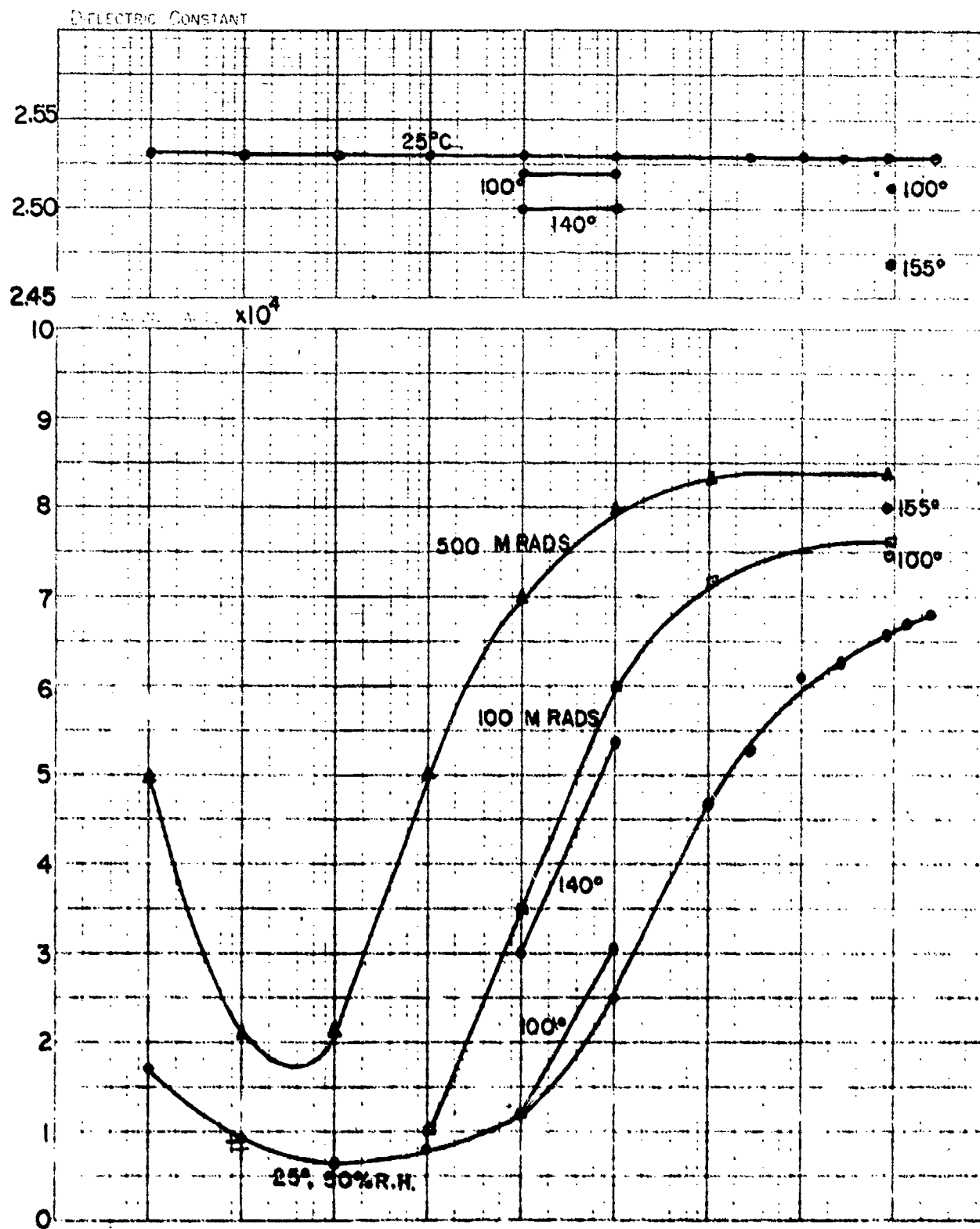
	10 <sup>5</sup> Hz		73°F	
	$\kappa$	$\tan \delta$	10 <sup>6</sup> Hz	$\tan \delta$
<u>Resin 100 parts</u>				
ERL-4221 <sup>a</sup>	3.42	.0145	3.33	.0165
ERL-4221/ERRA-4090 <sup>b</sup>	4.13	.0193	4.05	.0233
ERL-4289 <sup>c</sup>	3.40	.0123	3.34	.0160
ERL-4259 <sup>d</sup>	3.93	.0172	3.82	.0151
ERL-4259 <sup>e</sup>	3.44	.0159	3.33	.0234
ERL-4221/ERRA-4090 <sup>f</sup>	3.84	.0175	3.74	.0153
CY-178 <sup>g</sup>	3.38	.0177	3.31	.0179
ERL-4221/ERRA-4090 <sup>h</sup>	4.52	.0302	4.42	.0270

- a. 90 parts HHPA, 0-silica.
- b. 65 parts HHPA, 0-silica.
- c. 65-HHPA, 0-silica.
- d. 65-HHPA, 115-silica.
- e. 90 parts hardener liquid anhydride (Ciba), 0-silica.
- f. 65-HHPA, 85-silica.
- g. 65-HHPA, 0-silica.
- h. 65-HHPA, 118-silica.

Rexolite 1422 (1964),

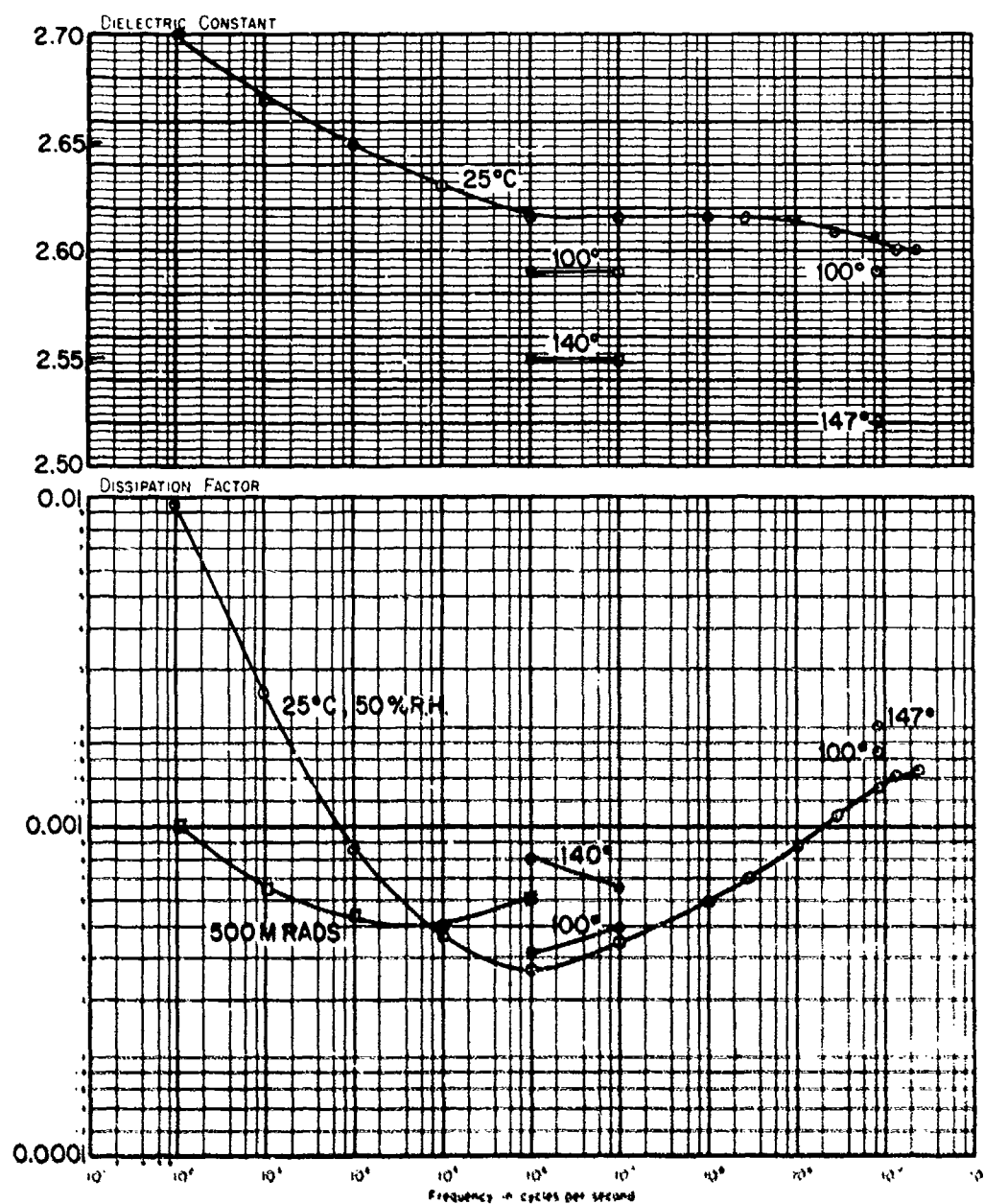
Wm. Brand Rex Division  
of American Enka Corp.

including effect of Van De Graaff irradiation (1960)



Rexolite 2200 (1964),

including effect of Van De Graaff irradiation (1960)

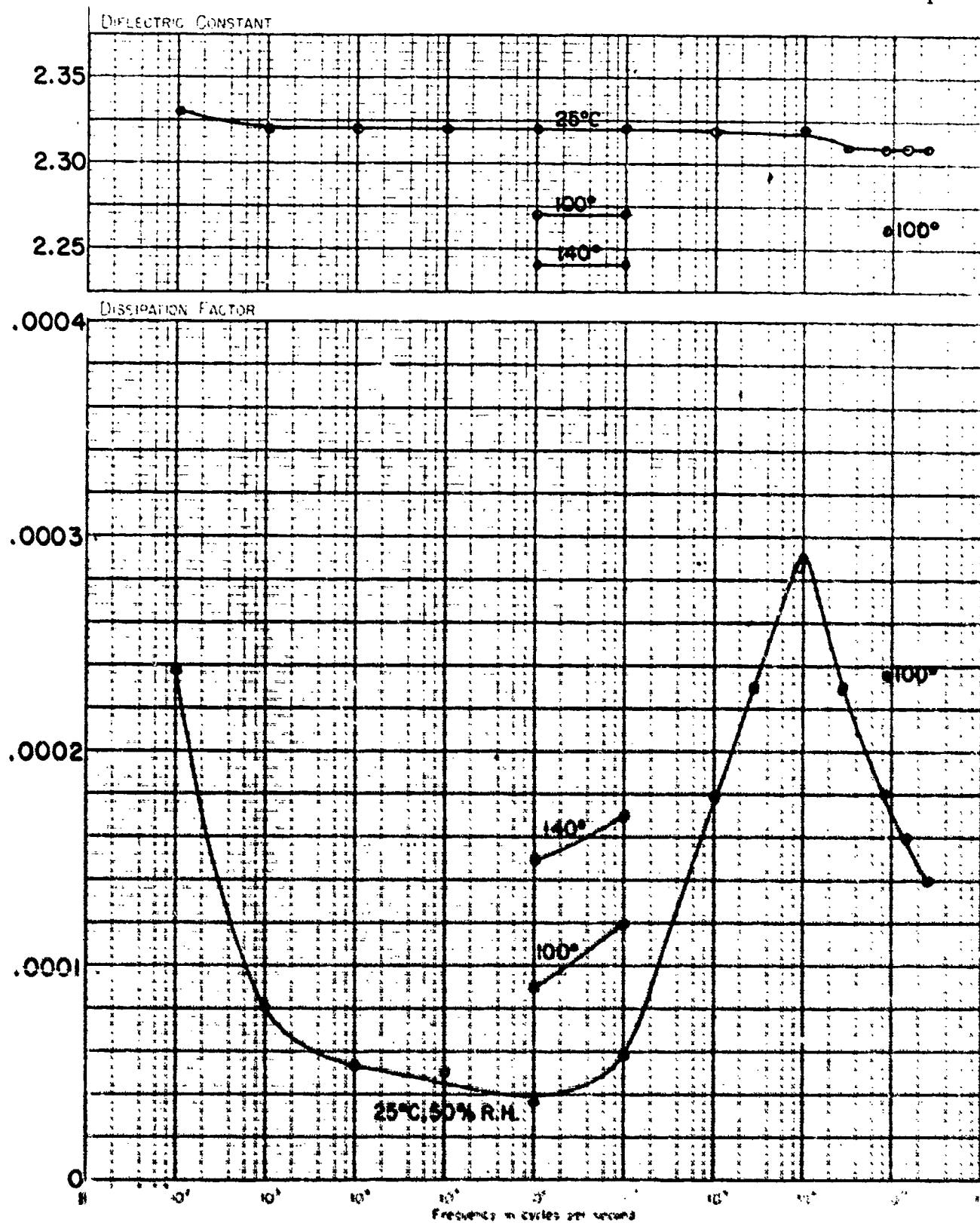


Rexolite 2200 (1965)

		3 GHz		8.52 GHz		% wt. increase
		$\kappa'$	$\tan \delta$	$\kappa'$	$\tan \delta$	
As received	25°C	2.65	.00169	2.65	.00170	
	-48°C			2.64	.00110	
	74°C			2.645	.00209	
After 24 hrs. H <sub>2</sub> O	25°C	2.66	.0026	2.66	.00343	.055

Rexolene P

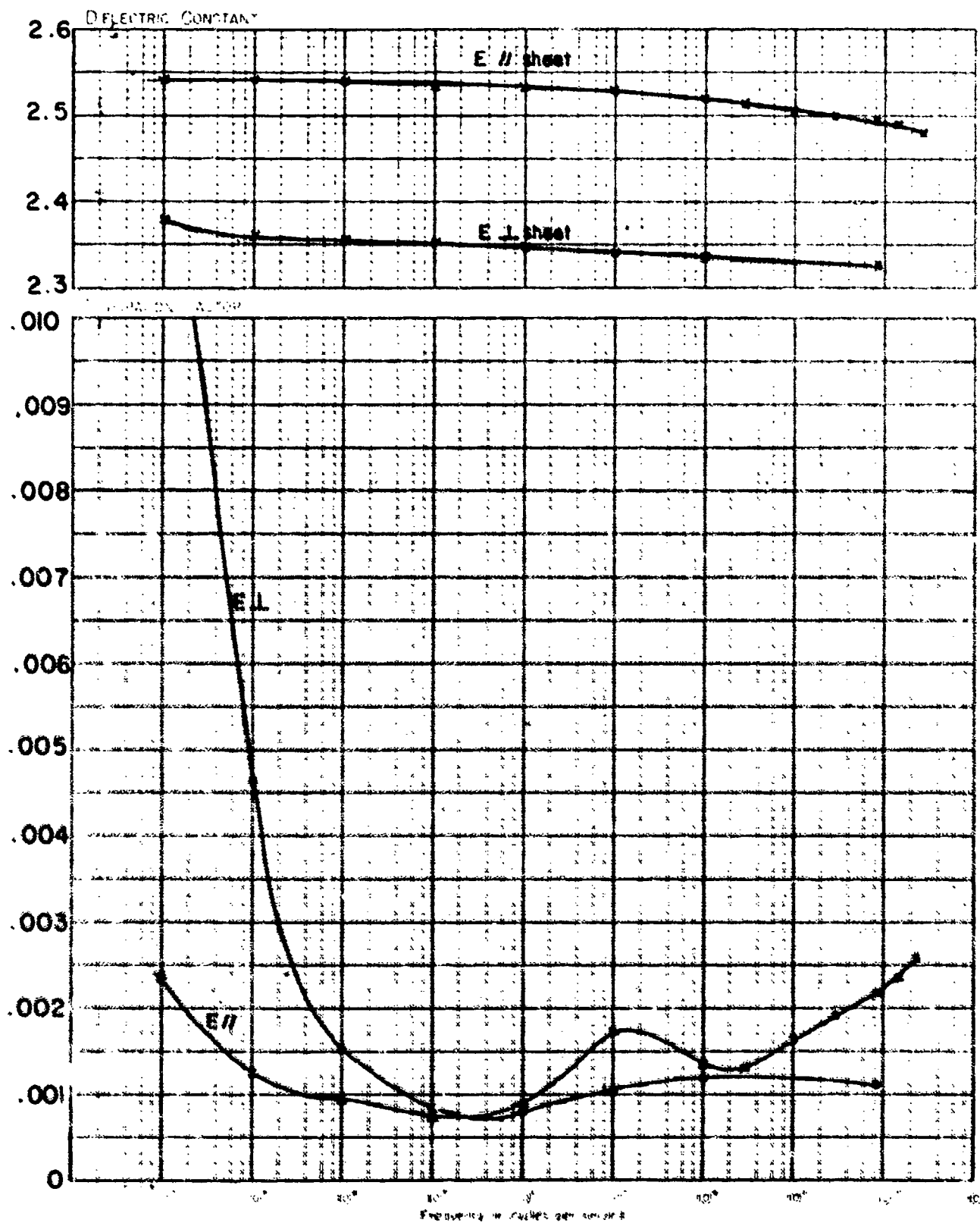
Wm. Brand Rex Division  
of American Enka Corp.



Duroid (1" thick sheet)

Rogers Corporation

T °C	3.7 GHz		4.3 GHz		Cavity length (inches)
	E //	$\tan \delta$	E $\perp$	$\tan \delta$	
25	2.476	.00156	2.317	.00125	2.015
81.5	2.458	.00176	2.301	.00153	2.042
106.8	2.447	.00178	2.289	.00140	2.055
125	2.438	.00176	2.282	.00142	2.067
152	2.425	.00166	2.268	.00149	2.083
176	2.412	.00160	2.255	.00155	2.106
202	2.399	.00159	2.239	.00167	2.127
250	2.370	.00165	2.203	.00202	2.159
310	2.301	.00182	2.130	.0024	2.320
362	2.031	.00225	1.878	.0015	2.869

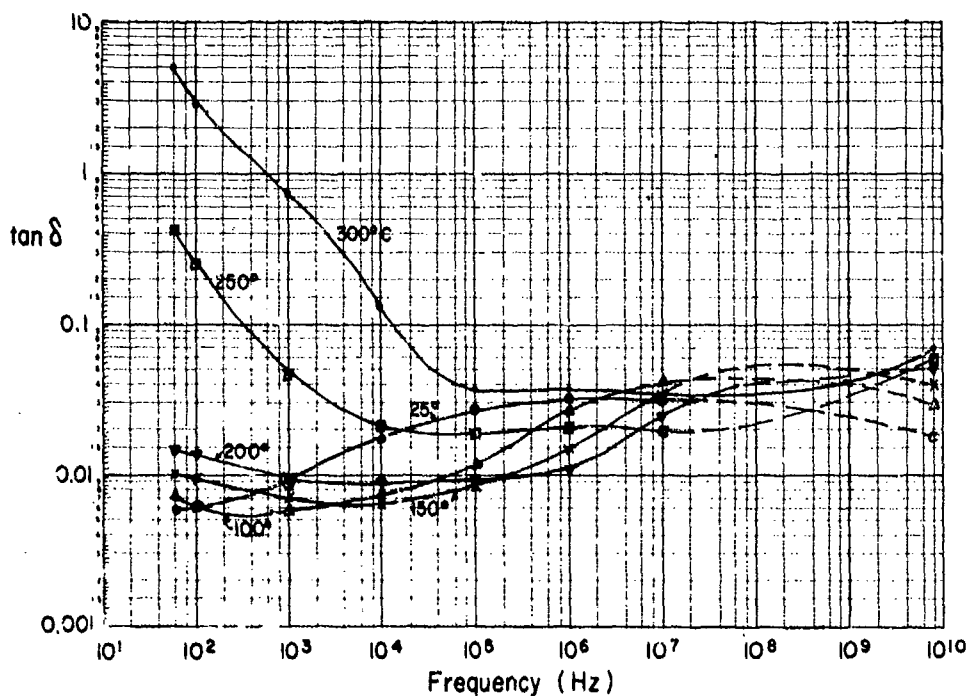
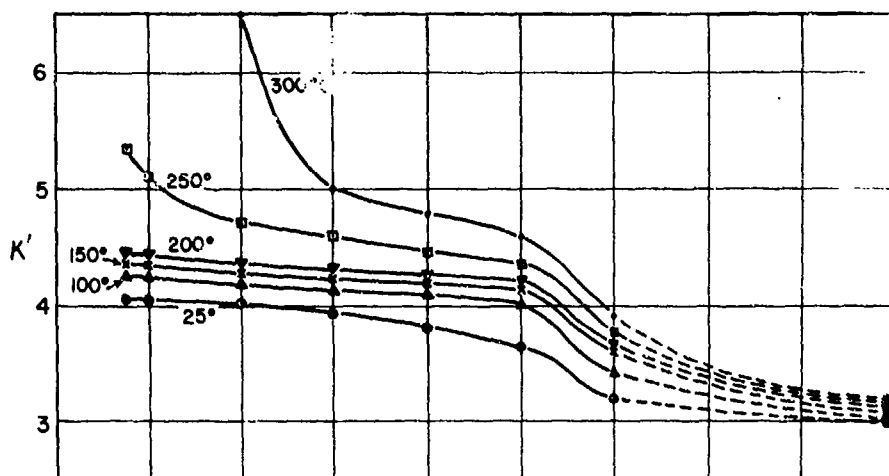




Epon 828/PMDA casting

Shell Chemical Company

156 pts. { Epon 828 epoxy 100 pts. by weight  
PMDA (pyromellitic dianhydride) 56 pts. by weight  
plus  
20 pts. { Tetrahydrofurfural alcohol 99 pts. by weight  
Dicyandiarnide 1 pt. by weight

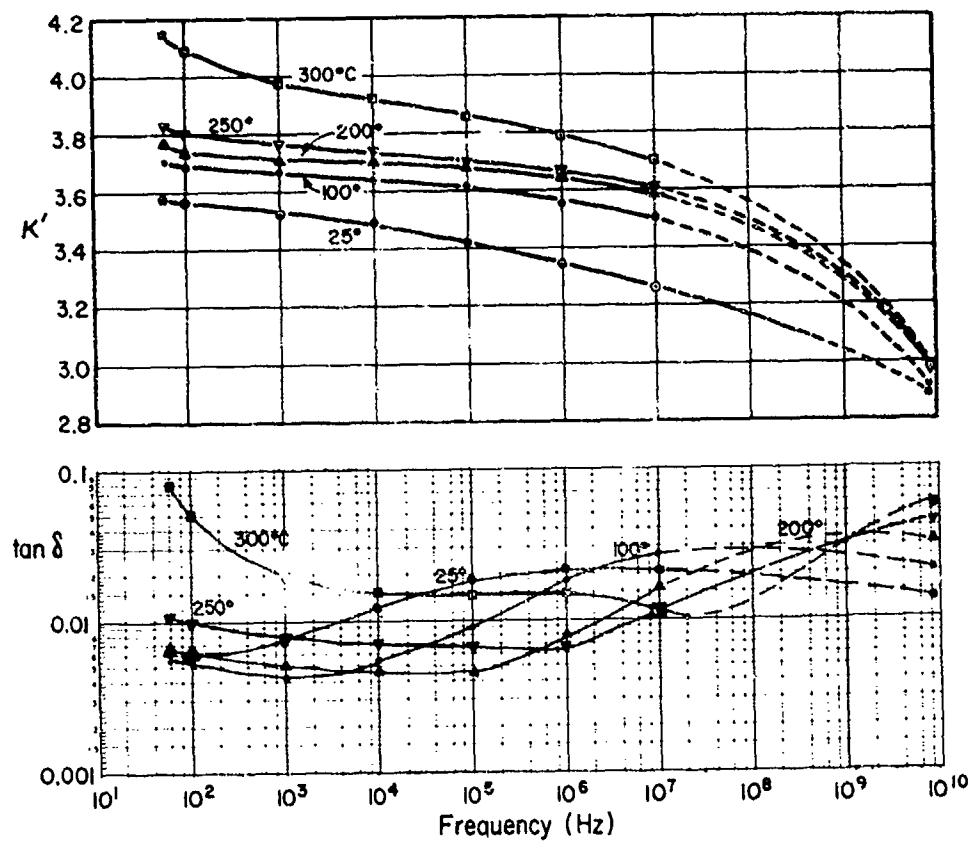


Epon 828/PMDA casting

Shell Chemical Company

Epon 828 epoxy 100 pts. by weight

PMDA (pyromellitic dianhydride) 31 pts. by weight



Polystyrene foam  
Polyurethane foam

The Sippican Corporation

Sample	Hz	$5 \times 10^4$	$10^6$	$6 \times 10^7$	$3 \times 10^8$	$1 \times 10^9$
I, white polystyrene $\kappa$		1.060	1.060	1.060	1.058	1.057
3 lbs/cu.ft. D.F.		.000083	<.00002	<.0002	.00004	<.00005
II, blue polystyrene $\kappa$		1.0368	1.0367	1.037	1.037	1.037
2 lbs/cu.ft. D.F.		.000061	<.00002	<.0002	.0001	<.00005
III, polyurethane $\kappa$		1.0846	1.082	1.080	1.078	1.077
4 lbs/cu ft. D.F.		.00143	.00151	.0018	.00164	.00208
IV, polyurethane $\kappa$		1.155	1.148	1.145	1.144	1.143
6 lbs/cu.ft. D.F.		.00207	.00289	.0033	.00295	.00347

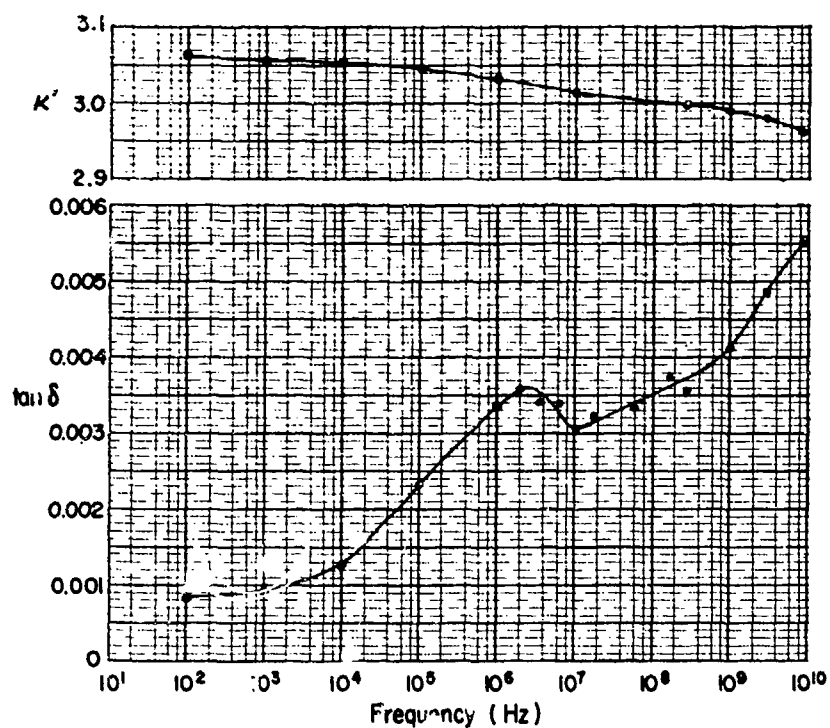
Tellite 3A

Tellite Corp.

	T <sup>o</sup> C	$\kappa'$	$\tan \delta$	$\kappa'$	$\tan \delta$	% weight increase
As received	25	2.31	.00028	2.311	.00022	
	-48			2.318	.00020	
	74			2.294	.00027	
After 24 hrs H <sub>2</sub> O	25	2.31	.00036	2.311	.0003~	.003

Polysulfone, 25°C, 50% R. H.

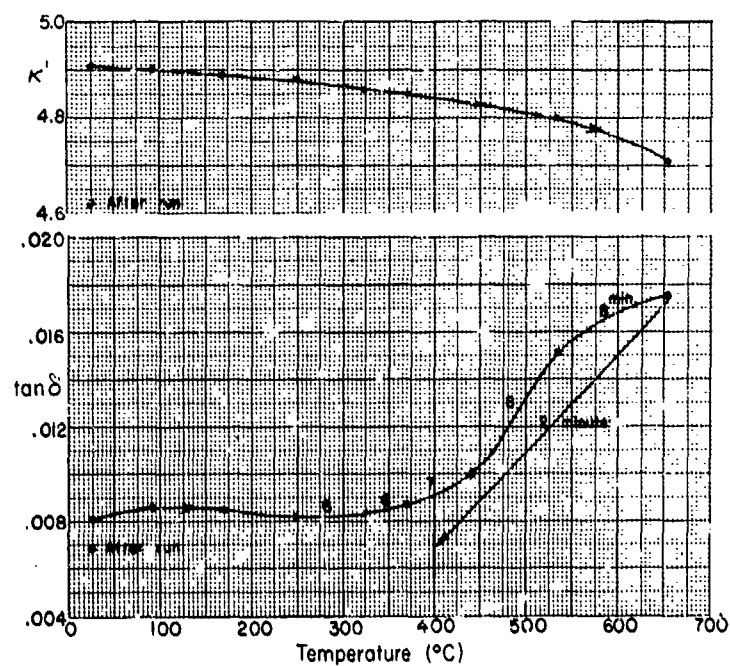
Union Carbide Corp.  
Plastics Division



Fiberglass laminate

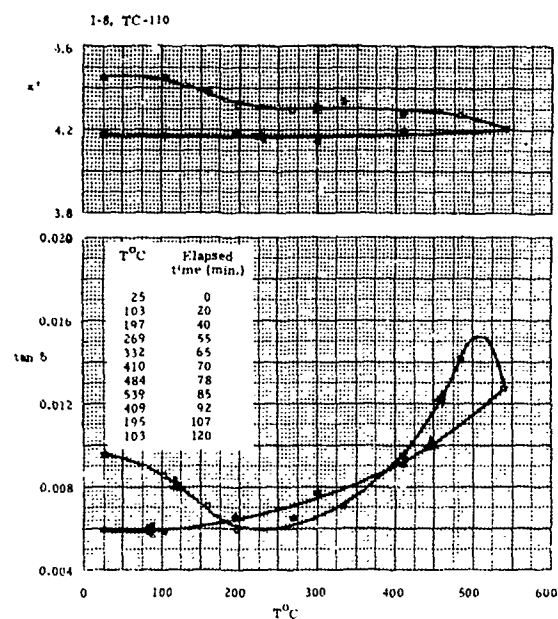
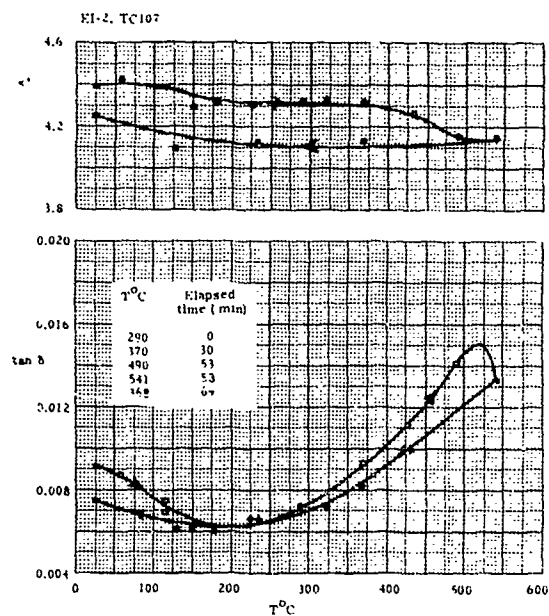
Air Force Materials Laboratory

with polybenzimidazole resin (approx. 24%)  
density 1.949 g/cm<sup>3</sup>



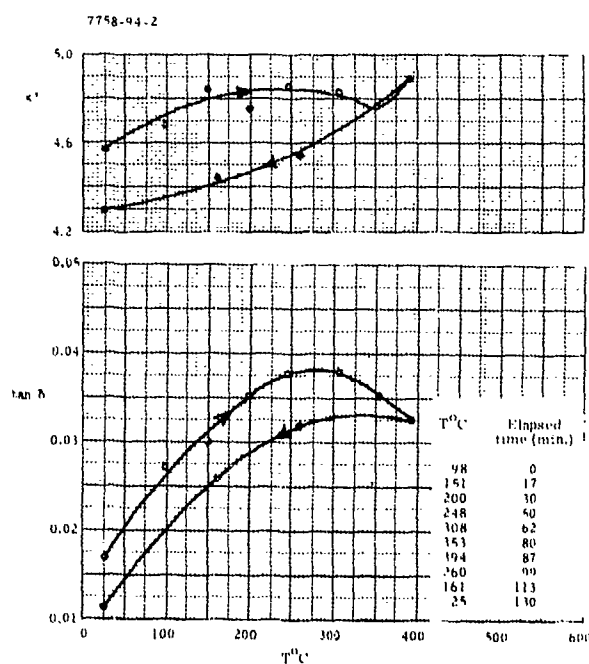
# Fiberglass laminates

# Air Force Materials Laboratory



Fiberglass laminate with 181 glass cloth and a polyol cross-linked polyimide resin, 8.52 GHz

Fiberglass laminate with 181 glass cloth and a polyimide resin, 8.52 GHz



Fiberglass laminate with 181 glass cloth and epoxy resin, 8.52 GHz

# IV. MISCELLANEOUS ORGANICS

Coal, powdered

Peabody Coal Division  
Kennecott Copper

Room humidity, 8.5 GHz

Sample No.	$\kappa'$	$\kappa''$	$\tan \delta$	$\sigma$ (ohm-cm) <sup>-1</sup>	$\rho$ (g/cm <sup>3</sup> )
1-421	4.65	.892	.191	4.22x10 <sup>-3</sup>	.780
1-422	5.85	1.21	.206	5.73	.842
1-424	5.76	1.15	.199	5.42	.813
0-1071	4.84	1.02	.209	4.81	.759
1-429	4.33	.800	.184	3.68	.768
1-436	5.23	1.11	.211	5.24	.756
1-423	5.17	1.13	.217	5.35	.740
1-427	5.07	1.09	.215	5.17	.759
1-425	4.66	.885	.189	4.18	.792
0-1075	4.16	.788	.189	3.73	.775

Sample No.	Freq., Hz	10 <sup>2</sup>	10 <sup>3</sup>	10 <sup>4</sup>	10 <sup>5</sup>	10 <sup>6</sup>	10 <sup>7</sup>
1-421	$\kappa'$	1626.	123.	40.8	21.1	15.5	9.11
$\rho=.850$	$\kappa''$	10886.	1122.	153.	24.2	9.56	3.02
	$\tan \delta$	6.69	9.10	3.75	1.14	.613	.331
	$\sigma$	6.0E-7	6.2E-7	8.5E-7	1.3E-6	5.3E-6	1.6E-5
1-422	$\kappa'$		720.	100.	39.4	18.7	11.1
	$\kappa''$		7368.	930.	92.8	18.8	5.12
$\rho=.850$	$\tan \delta$		10.2	9.28	2.36	1.01	.462
	$\sigma$		4.1E-6	5.1E-6	5.1E-6	1.0E-5	2.7E-5

Coal, single lump

Massachusetts Institute of Technology  
National Magnet Laboratory

Frequency, Hz	$10^6$	$8.5 \times 10^9$
$\kappa'$	-	8.4
$\kappa''$	-	2.47
$\tan \delta$	-	.294
$\sigma$	$1 \times 10^{-4}$	.117

Balsa wood

The Sippican Corporation

Frequency, MHz	$\kappa$	$\tan \delta$
0.05	2.190	.123
1	1.928	.0614
60	1.727	.0620
300*	1.417	.046
1000*	1.404	.047

\*) Electric field grain, others E along grain

## Particle boards

The Sippican Corporation

<u>Sample</u>	Freq., Hz	E $\perp$ sheet		E $\parallel$ sheet	
		$5 \times 10^4$	$10^6$	$3 \times 10^8$	$10^9$
1. U.S. Plywood fiber face	$\kappa$ tan $\delta$	3.16 .0345	2.94 .0410	2.91 .109	2.69 .105
2. U.S. Plywood fiber face, all phenolic	$\kappa$ tan $\delta$	3.48 .0745	3.02 .0582	2.85 .102	2.66 .096
3. U.S. Plywood Novoply	$\kappa$ tan $\delta$	3.12 .0261	2.98 .0320	2.87 .099	2.67 .100
4. Evans Products, MDF	$\kappa$ tan $\delta$	3.32 .0230	3.20 .0368	3.08 .106	2.85 .101
5. Evans Products, underlayment grade	$\kappa$ tan $\delta$	3.26 .0229	3.13 .0360	3.00 .110	2.76 .104

## Wood products

The Sippican Corporation

25°C, E in plane of sheet							
<u>Material</u>	Freq., Hz	$5 \times 10^4$	$5 \times 10^5$	$3 \times 10^6$	$1.8 \times 10^7$	$3 \times 10^{7*})$	$3 \times 10^8$
Pine board	$\kappa$ tan $\delta$	2.90 .0228	2.81 .037	2.68 .055	2.38 .081	2.31 .087	2.06 .090
Fir plywood	$\kappa$ tan	3.18 .060	2.97 .068	2.78 .064	2.54 .064	2.47 .065	2.25 .074
Birch plywood	$\kappa$ tan	2.87 .033	2.74 .041	2.62 .0505	2.38 .062	2.32 .063	2.16 .067
Marinite	$\kappa$ tan	2.88 .49	2.33 .148	2.07 .054	2.00 .0219	1.98 .020	1.910 .0200

\*) Values at 30 MHz are interpolated, not measured.



# V. LIQUIDS

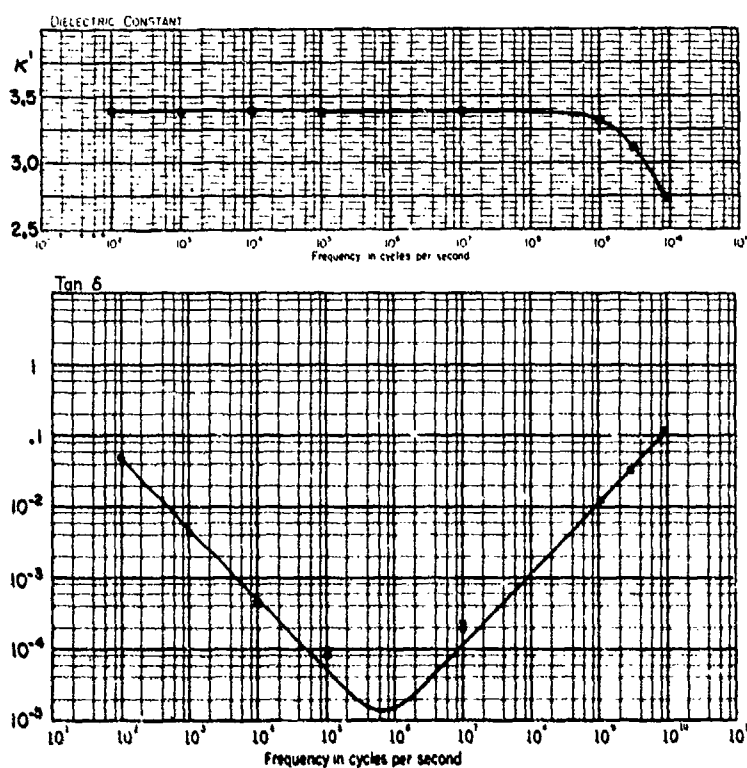
Fluorocarbon derivative P-1C  
At 25°C

Allied Chemical Corporation

Freq. (GHz)	$\kappa$	$\tan \delta$
1	1.92	.0050
3	1.92	.0140
8.52	1.89	.029
14	1.87	.038

Dowtherm A

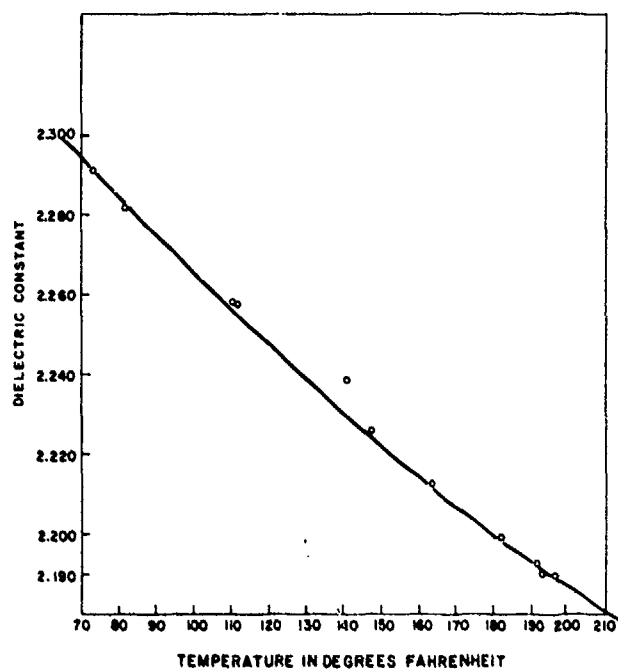
Dow Chemical



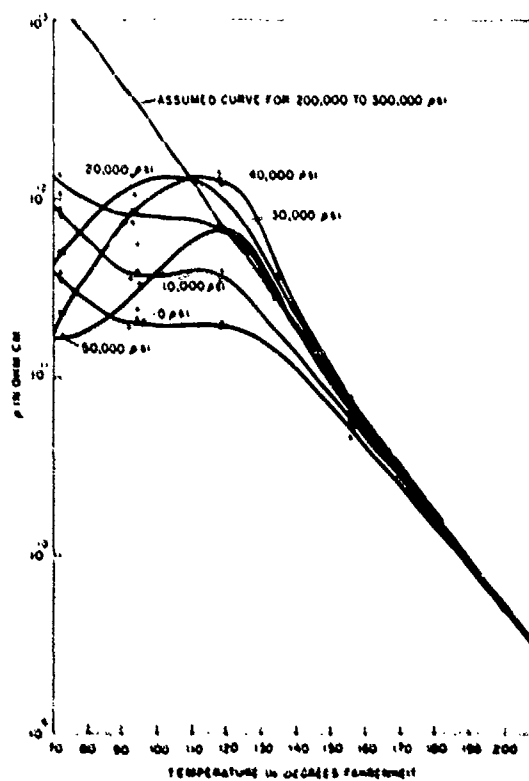
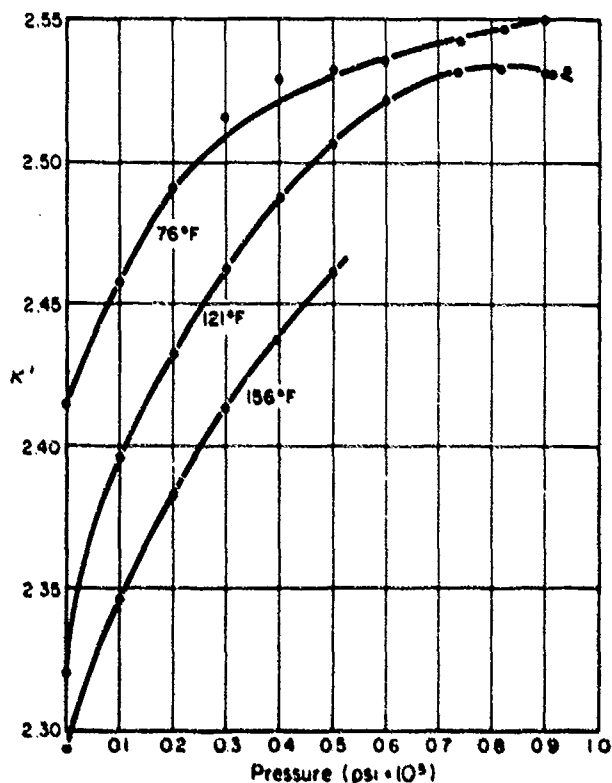
Fluorinated ethers, at 27°C  
TOC = <6 to 28

E. I. Dupont de Nemours & Co.

Freq. (Hz)	FPS-1418		FPS-1419		FPS-1420	
	b.p. 148°C $\kappa$	$\tan \delta$	b.p. 101°C $\kappa$	$\tan \delta$	b.p. 153°C $\kappa$	$\tan \delta$
$10^2$	1.890	$3 \times 10^{-6}$	1.859	$1.6 \times 10^{-5}$	2.570	$3.23 \times 10^{-3}$
$10^5$	1.890	$3 \times 10^{-6}$	1.859	$2 \times 10^{-6}$	2.570	$1.6 \times 10^{-5}$
$10^8$	1.888	.00243	1.857	$4.2 \times 10^{-4}$	2.53	.0126
$10^9$	1.851	.0142	1.833	.0042	2.420	.0952
$3 \times 10^9$	1.838	.0124	1.832	.0075	2.213	.0995
$8.5 \times 10^9$	1.797	.0068	1.798	.0084	2.026	.0907



Teresso V-78 (cont.)



Hercules, Inc.

DI-CUP  
dicumyl peroxide

25°C

$\kappa$	$\tan \delta$
2.79	.0073
↓	.00081
	.000115
	.000064
	.00040
	.0032
2.97	.0025
2.73	.0050
2.70	.0082
2.57	.0078
2.515	.0044
2.495	

VUL-CUP  
a,a<sup>1</sup>-bis(t-butyl peroxy) diisopropylbenzene

25°C

Freq., Hz	$\kappa$	$\tan \delta$
10 <sup>2</sup>	2.633	.0011
10 <sup>3</sup>	↓	.00011
10 <sup>4</sup>		.000013
10 <sup>5</sup>		10 <sup>-5</sup>
10 <sup>6</sup>		.00005 ± 2
1.8x10 <sup>7</sup>		
6x10 <sup>9</sup>	2.63	.005 ± 2
10 <sup>8</sup>	2.60	.0206
10 <sup>9</sup>	2.56	.0378
3x10 <sup>9</sup>	2.40	.056
8.5x10 <sup>9</sup>		

99°C

10 <sup>9</sup>	2.26	.0116
3x10 <sup>9</sup>	2.24	.0184

Pennwalt Corp., Lucidol Div.

Lucidol  
t-butyl perbenzoate

25°C

Freq., Hz	$\kappa$	$\tan \delta$
10 <sup>2</sup>	-	-
10 <sup>3</sup>	-	-
10 <sup>4</sup>	12.17	.17
10 <sup>5</sup>	12.17	.017
10 <sup>6</sup>	12.1	.0027
10 <sup>7</sup>	12.0	.0095
10 <sup>8</sup>	11.2	.0044
10 <sup>9</sup>	5.70	.252
3x10 <sup>9</sup>	4.07	.337
8.5x10 <sup>9</sup>	3.23	.460

Lupersol 130  
2,5 dimethyl-2,5-di(t-butylperoxy)hexyne-3

25°C

Freq., Hz	$\kappa$	$\tan \delta$
10 <sup>2</sup>	2.656	.00123
10 <sup>3</sup>	↓	.000123
10 <sup>4</sup>		.000012
10 <sup>5</sup>		.000023
10 <sup>6</sup>		.00012
10 <sup>7</sup>	2.655	.00121
10 <sup>8</sup>	2.65	.0066
10 <sup>9</sup>	2.56	.0235
3x10 <sup>9</sup>	2.50	.0344
8.5x10 <sup>9</sup>	2.39	.0505

99°C

2.33	.0076
2.32	.0154

## Mullet oil

Freq., GHz	24 ± 0.5°C	
	κ	tan δ
1	2.54	.068
8.5	2.52	.0507
14	2.42	.0468
24		.0384

## U.S. Bureau of Fisheries

	10 ± 1°C	
	κ	tan δ
	-	-
	2.50	.0458
	2.39	.0443
	2.36	.0380

## USP 333

## U.S. Peroxygen Div., Argus Chemical Corp.

Freq., Hz	25°C	
	κ	tan δ
10 <sup>2</sup>	3.818	.0170
10 <sup>3</sup>	↓	.00170
10 <sup>4</sup>		.00017
10 <sup>5</sup>		.000027
10 <sup>6</sup>		.00021
10 <sup>7</sup>	3.81	.00157
10 <sup>8</sup>	3.75	.0146
10 <sup>9</sup>	3.60	.0842
3x10 <sup>9</sup>	3.30	.130
8.5x10 <sup>9</sup>	2.80	.1735

## Lupersol 101

## Wallace &amp; Tiernan Inc.

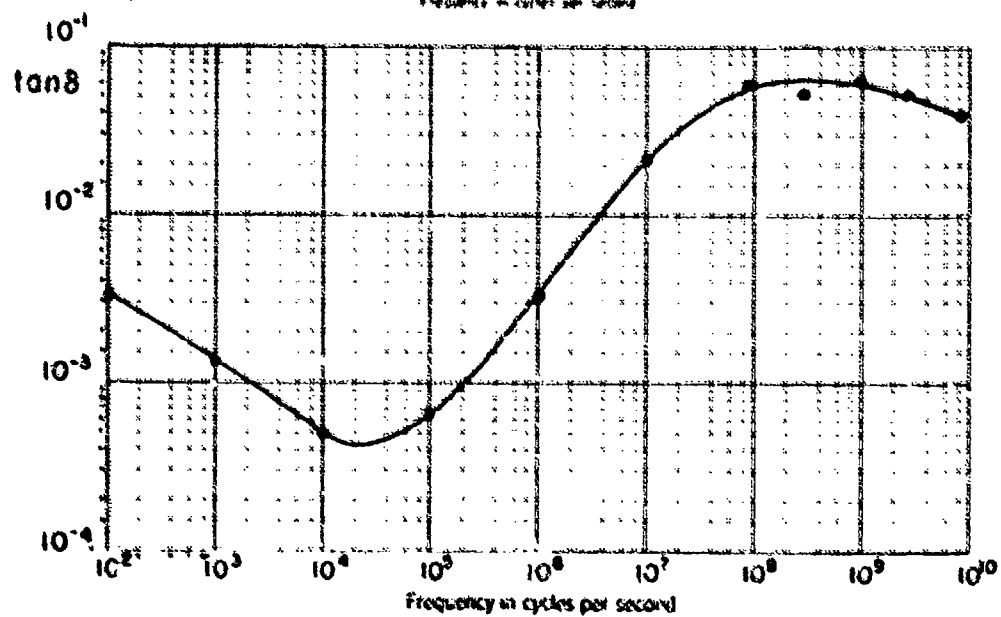
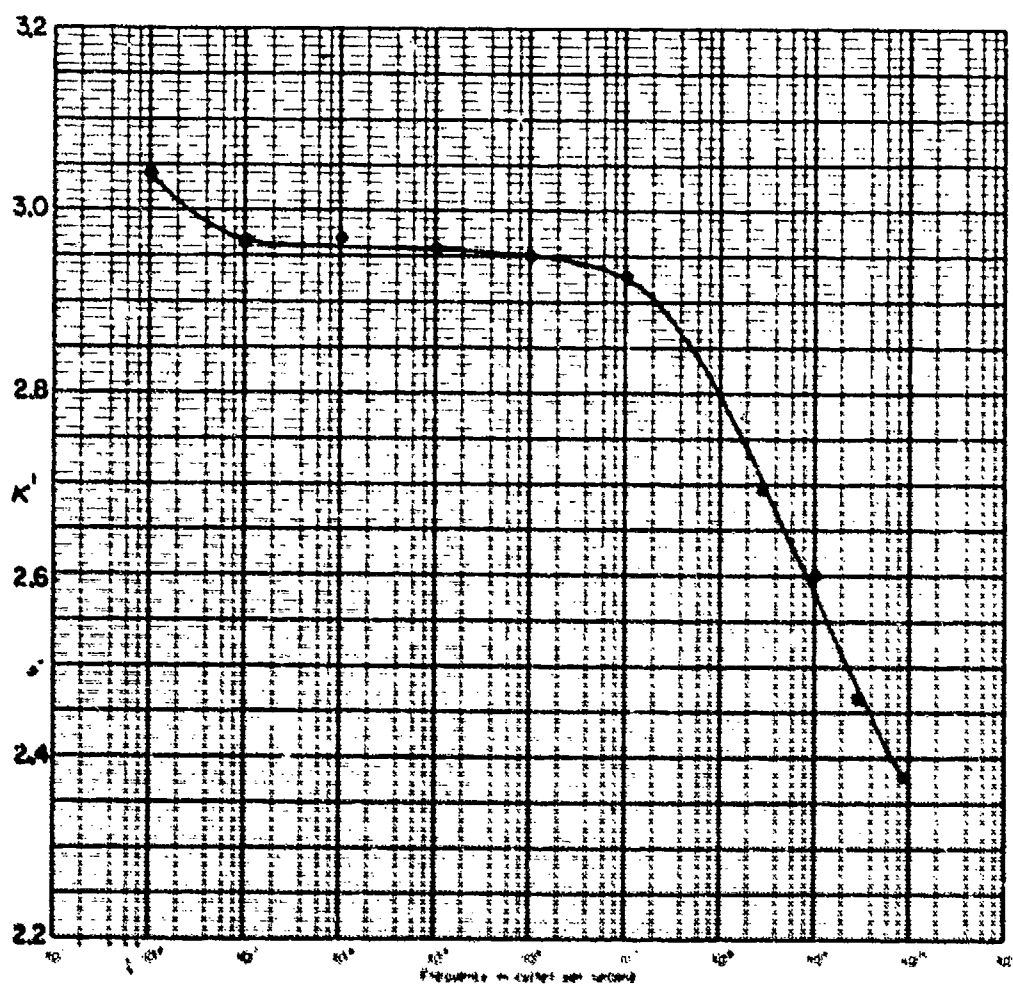
## 2,5-dimethyl-2,5-di(t-butylperoxy)hexane

at 25°C		
Freq., Hz	κ	tan δ
10 <sup>4</sup>	2.66	.000088
10 <sup>5</sup>	2.66	.000144
10 <sup>6</sup>	2.66	.000053
10 <sup>7</sup>	2.65	.00049
10 <sup>8</sup>	2.64	.0050
10 <sup>9</sup>	2.62	.0217
3x10 <sup>9</sup>	2.58	.0387
8.5x10 <sup>9</sup>	2.41	.057
2.4x10 <sup>10</sup>	2.26	.045
at 99°C		
10 <sup>9</sup>	2.02	.0040
3x10 <sup>9</sup>	2.02	.0068

# VI. FOODSTUFFS

Kremax

Armour



### Frozen lean steak

T°F	150 MHz		1000 MHz		3000 MHz	
	K	tan $\delta$	K	tan $\delta$	K	tan $\delta$
-75	3.42	.022	3.33	.0164	3.22	.0105
-60	3.61	.040	3.42	.026	3.40	.014
-50	3.70	.058	3.46	.036	3.44	.0185
-40	3.82	.072	3.51	.050	3.46	.024
-30	3.92	.094	3.60	.066	3.55	.032
-20	4.18	.102	3.80	.089	3.70	.040
-10	4.50	.138	4.10	.12	3.80	.054
0	5.33	.18	4.40	.165	3.95	.076
10	6.35	.24	5.18	.223	4.37	.108
20	9.55	.39	9.50	.203	7.30	.174
30	33	.60	20.8	.254	8.40	.250
40	53.5	.22	33.0	.32	8.30	.208
50	53.0	.21				

### Vacuum-dry lean beef

-60			1.495	.00320	1.471	.00335
-40	1.535	.0060	1.497	.00375	1.473	.00395
-20	1.548	.0080	1.502	.00446	1.475	.0047
0	1.562	.0102	1.511	.00535	1.480	.0057
20	1.582	.0132	1.520	.0066	1.483	.0068
40	1.60	.0168	1.530	.0080	1.490	.0082
60	1.62	.0216	1.542	.0096	1.500	.0099
80	1.648	.0264	1.558	.0111	1.509	.0119
100			1.571	.0127	1.522	.0138
120			1.587	.0143	1.535	.0147
140			1.604	.0160	1.545	.0175
160			1.622	.0176	1.560	.0193
180			1.642	.0198	1.590	.0214

### Potato (Maine, 78.9% H<sub>2</sub>O), 25°C

f (GHz)	K'	tan $\delta$
.3	130	.83
1	87	.39
3	81	.38

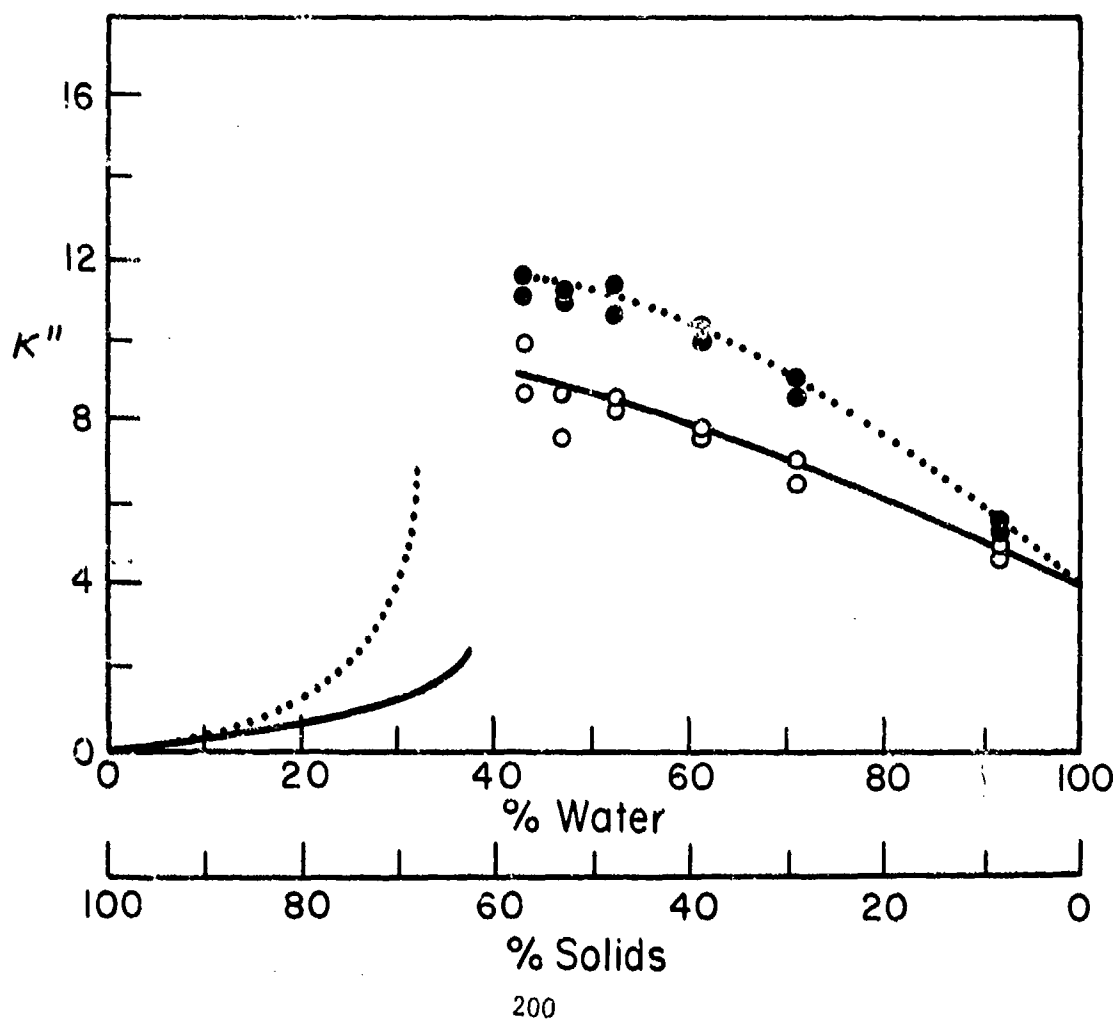
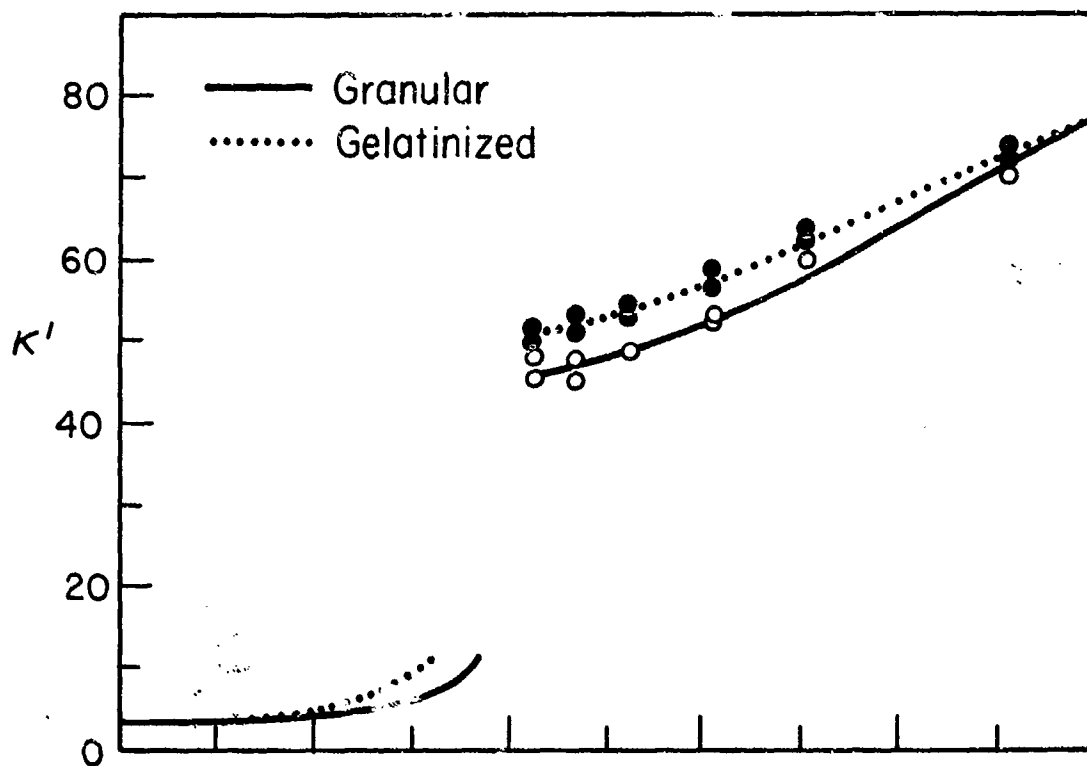
### Potato flakes, density 0.284

.3	1.50	.034
1	1.485	.030
3	1.47	.029

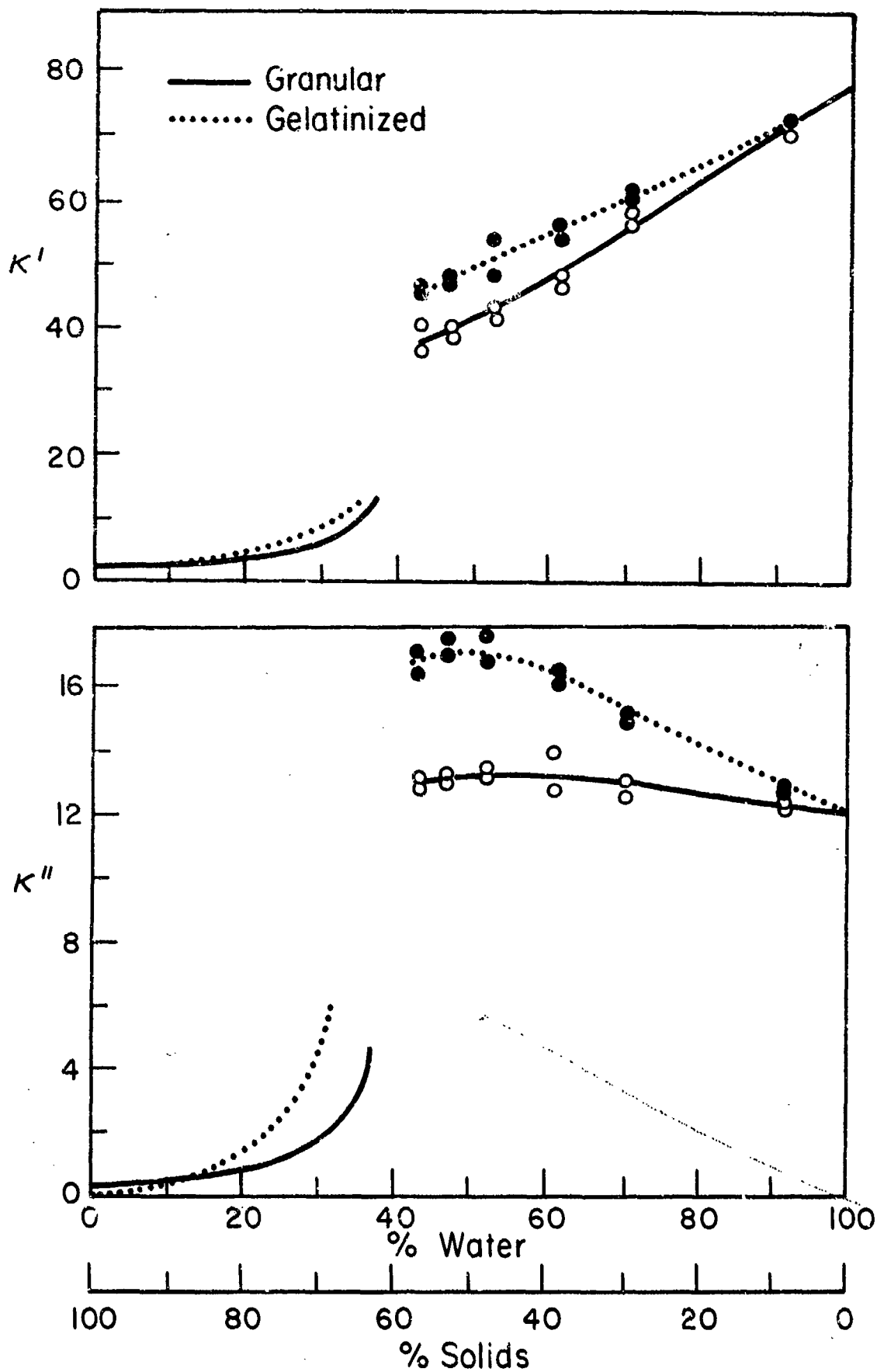
### Potato chips

partly cooked	1	5.76	.36
	3	5.18	.55
cooked	1	1.89	.034
	3	1.86	.036

Potato starch,  
granular and gelatinized, at 10 GHz, 25°C



Potato starch,  
granular and gelatinized, at 3.0 GHz, 25°C





Nescafe				Nestea		
f (Hz)	$\kappa'$	$\tan \delta$	$\sigma$	$\kappa'$	$\tan \delta$	$\sigma$
$10^2$	1.557	.0115	$9.93 \times 10^{-13}$	1.290	.00442	$3.17 \times 10^{-13}$
$10^3$	1.529	.0113	$9.58 \times 10^{-12}$	1.281	.00384	$2.73 \times 10^{-12}$
$10^4$	1.490	.0103	$8.52 \times 10^{-11}$	1.276	.00301	$2.13 \times 10^{-11}$
$10^5$	1.488	.0090	$7.43 \times 10^{-10}$	1.270	.00245	$1.73 \times 10^{-10}$
$10^6$	1.471	.0089	$7.27 \times 10^{-9}$	1.267	.00230	$1.62 \times 10^{-9}$
$10^7$	1.453	.0093	$7.52 \times 10^{-8}$	1.260	.00196	$1.37 \times 10^{-8}$
$3 \times 10^8$	1.432	.0106	$2.53 \times 10^{-7}$	1.24	.0023	$4.75 \times 10^{-7}$
$10^9$	1.39	.0098	$7.57 \times 10^{-6}$	1.22	.0024	$1.63 \times 10^{-7}$
$3 \times 10^9$	1.36	.0093	$2.11 \times 10^{-5}$	1.21	.0026	$5.25 \times 10^{-6}$
$8.5 \times 10^9$	1.34	.0086	$5.65 \times 10^{-5}$	1.20	.0033	$1.87 \times 10^{-5}$
density 0.241 g/cm <sup>3</sup>				0.126 g/cm <sup>3</sup>		

#### Eggwhite

Frequency	$\kappa'$	$\tan \delta$	$\rho$
$3 \times 10^9$	35	.5	
$9.2 \times 10^9$	13	1.1	
$10^4, 10^5$			35

#### Bread

$1.2 \times 10^7$	11	3.35	
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#### Dough

$10^7$	$2 \times 10^5$	2.25	1
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